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Planning Methodologies for Analysis of Land Use/Water Quality Relationships

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PLANNING METHODOLOGIES FOR ANALYSIS OF LAND USE / WATER QUALITY RELATIONSHIPS

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PLANNING METHODOLOGIES FOR ANALYSIS OF LAND USE/WATER QUALITY RELATIONSHIPS

by

Thomas R. Hammer, Ph.D.

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

DATE: DEC 3 1976

SUBJECT: Planning Methodologies for Analysis of Land Use/Water Quality Relationships

Walter S Groszyk

FROM: Edmund Notzon, Acting Director
Water Planning Division (WH-554)

TO: All Regional Water Division Directors

ATTN: Regional 208 Coordinators

Technical Guidance Memorandum: TECH-24

Purpose

This memorandum transmits the recently completed report, "Planning Methodologies for Analysis of Land Use/Water Quality Relationships." It is intended for use by state and areawide agencies in the development of their water quality management programs.

Guidance

This report evaluates the potential usefulness and practicality of various planning methodologies which can be used to quantitatively determine the relationship between land use and water quality. It also evaluates various land use and land management controls which can be used to reduce pollutant loadings. In carrying out these evaluations, the report reviews much of the current literature on the relationship between land use and water quality.

While the report examines various land uses, it is intended to focus on land uses commonly found in developed and developing areas. It is also intended to focus on stormwater related pollution sources in such areas. As a result municipal and industrial point sources as well as nonurban nonpoint sources are treated peripherally.

After evaluating a range of planning methodologies and control measures, the report examines the analysis and control of pollutants resulting from hydrologic modifications, on-lot disposal systems, and construction activity. These pollutant sources were chosen for in-depth examination because it is felt that they are major sources of pollution which can be prevented and which occur in many areas of the country.

The Office of Research and Development in conjunction with the Water Planning Division has recently published related guidance, the Areawide Assessment Procedures Manual. The manual differs from this report on

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planning methodologies in that it is more comprehensive, covering a range of point and nonpoint sources. The material presented in this report is intended to provide more detail on certain issues and in general to supplement the more comprehensive guidance presented in the manual.

If you would like further information on this report, please contact Bill Lienesch of the Program Development Branch (426-2522).

Enclosure

cc: State and Areawide Agencies

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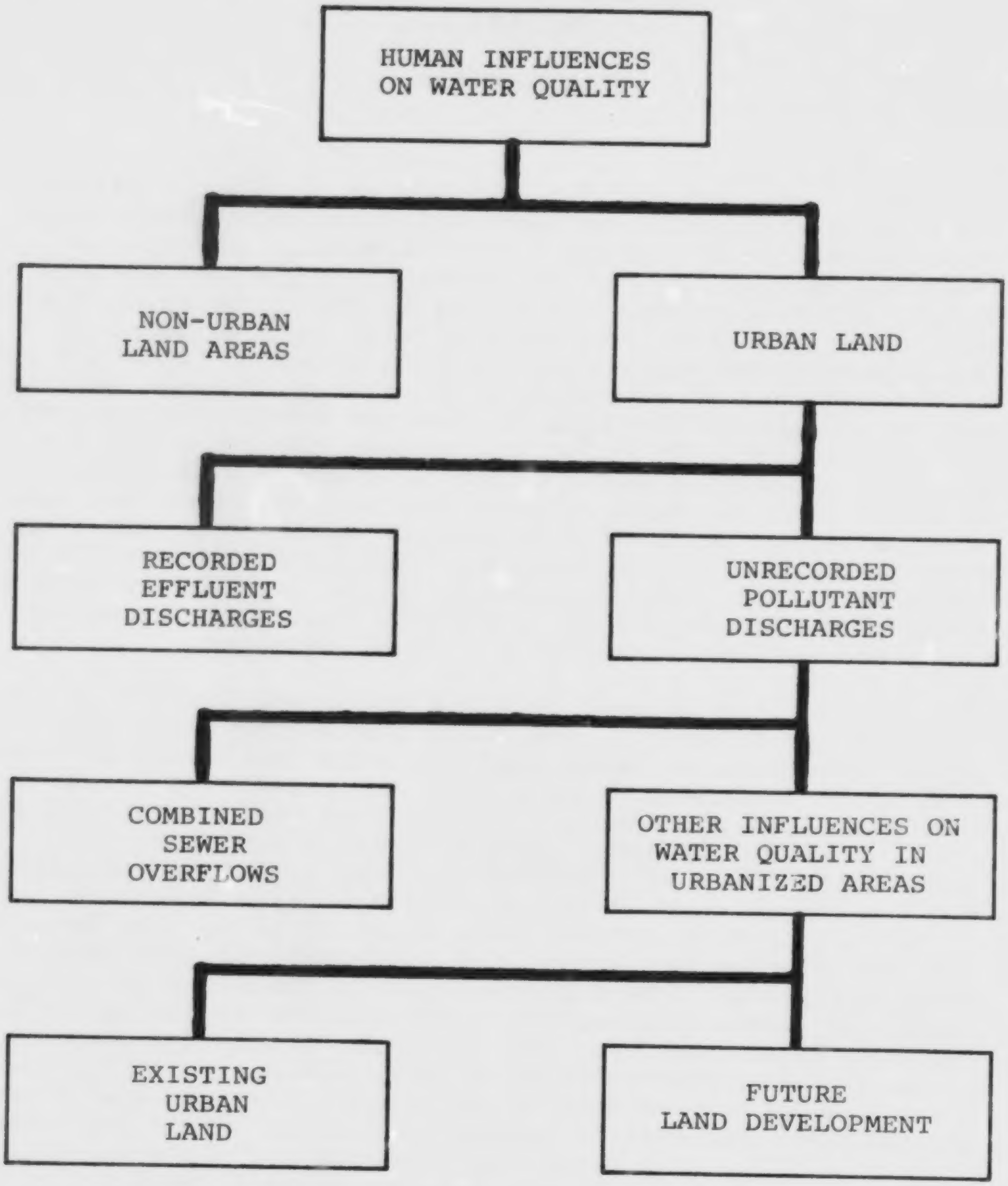
SECTION 1

INTRODUCTION

Past water quality control activity in the United States dealt primarily with treatment and disposal of wastewater from industry and municipal sewer systems. In contrast, a basic element of the current Federally-sponsored program of water quality management planning is the recognition that many other pollutant sources must also be considered if water quality objectives are to be achieved. It is now acknowledged that an extremely wide variety of human activities which affect the land surface can constitute sources of water pollution. In order to overcome the generally low level of experience which exists in dealing with these sources, the U.S. Environmental Protection Agency has sponsored a series of studies to provide guidance to state and areawide water quality management agencies. This study is one such effort. The present objective has been to develop a planning methodology for analyzing land/water relationships and evaluating possible control measures.

The scope of the present study of pollutant sources is illustrated in Figure 1. The study focuses strictly upon urban influences on water quality. The definition of urban land would include both developed and developing areas. Pollutant loadings involving urban land are categorized as either recorded or unrecorded effluent discharges. For present purposes, recorded sources can be defined as effluent discharges covered by National Pollutant Discharge Elimination System (NPDES) permits as of 1974. The main recorded sources are industrial and municipal treatment plant effluents. The present study is concerned with unrecorded pollutant discharges, which include all other influences on water quality. The principal mechanisms whereby unrecorded pollution occurs in urban areas are the following: washoff and erosion of materials from land surfaces; unauthorized disposal of wastes in surface waters and storm sewers; outflow of contaminated groundwater (from on-site septic systems, landfills, and sewer leaks); overflow of municipal sewer systems; and hydrographic modification. The definition of recorded and unrecorded sources in terms of present coverage by NPDES permits is purely a practical distinction, which does not necessarily relate to the manner in which pollutants are conveyed to receiving waters.


HUMAN INFLUENCES ON WATER QUALITY
NON-URBAN LAND AREAS
URBAN LAND
RECORDED EFFLUENT DISCHARGES
UNRECORDED POLLUTANT DISCHARGES
COMBINED SEWER OVERFLOWS
OTHER INFLUENCES ON WATER QUALITY IN URBANIZED AREAS
EXISTING URBAN LAND
FUTURE LAND DEVELOPMENT

Source: Betz Environmental Engineers, Inc.

Figure 1 SCOPE OF THE PRESENT STUDY

An extremely important type of unrecorded pollutant source in many urban areas is combined sewer overflows. During storms, the inflow of surface runoff to combined sewer systems may cause the total wastewater flow to exceed system capacity; the resulting overflows deliver to receiving waters a mixture of untreated sewage, storm water pollutants, and materials which have accumulated in sewer pipes over time. Due to the attention which this problem has received in other studies, and the fact that it generally does not involve current types of urban development, the explicit focus of the present study is limited to areas _without_ combined sewers. However, the material presented is _relevant_ to pollutant loadings from combined sewer areas which originate from sources other than sanitary sewage overflow _per se_.

The final distinction noted in Figure 1 is between existing urban land and future urban development. A major emphasis of water quality management planning is the use of _preventive measures_ for urban water quality control, which can be integrated in the design of new land development projects. It is felt that preventive measures are likely to be much more cost-effective, and perhaps easier to implement, than remedial control measures which can be applied to urban land after development. The primary objective of the present study has been to provide assistance in designing and evaluating these preventive controls.

A fairly extensive review of unrecorded pollutant loadings and problems has been conducted as part of this study in order to address several critical issues which are discussed in the next section. The findings of this review are summarized here in Section 5, and are presented in detail in the Technical Appendix. A number of planning methodologies which have been developed by others are then evaluated in terms of their potential usefulness for water quality management planning. Based on this and other information, an overall strategy for dealing with the water quality impacts of new urban development is suggested, along with a general approach for analysis and control of existing problems. The specific methodologies which are recommended as planning tools are then discussed in detail in the final sections.

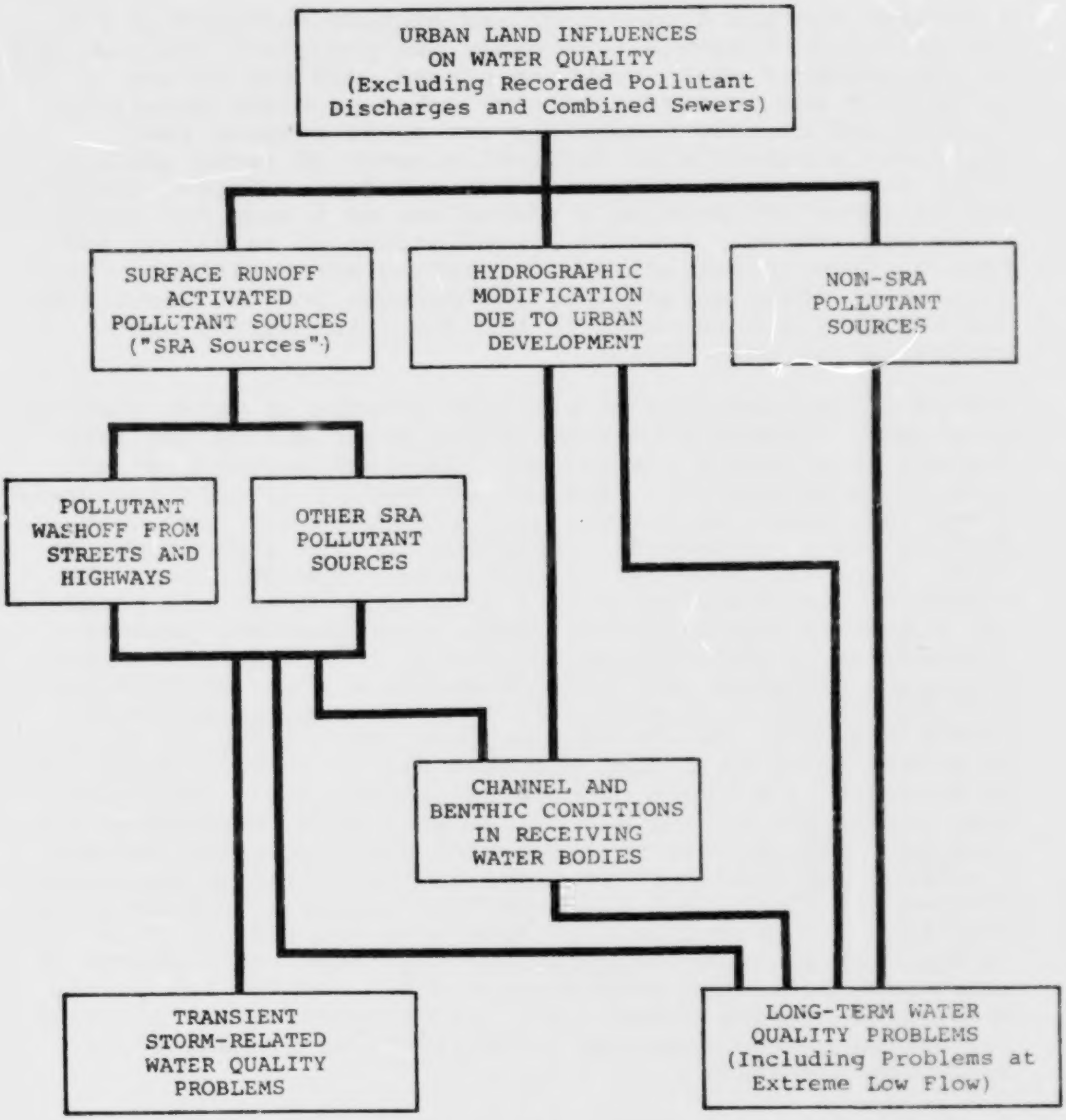
SECTION 2

SUMMARY

The present study has been undertaken with the goal of developing a planning methodology for use in urban water quality studies. To this end, four general classes of existing methodologies have been reviewed: (1) stormwater modeling, (2) environmental synthesis techniques, (3) statistical methods, and (4) other predictive tools. The planning approach for design of preventive controls which is ultimately recommended in this report stresses the use of a variety of single-purpose techniques rather than the first three of these classes of methodologies.

A viewpoint which developed in the course of the study is that the choice of a planning approach is critically dependent upon a number of underlying issues which do not appear to have received adequate attention in the literature. Much of the discussion in this report is therefore oriented toward these general issues, as opposed to the mechanics of applying specific planning methodologies. In order to describe these issues briefly here, a categorization of relevant water quality problems is presented in Figure 2.

As shown in Figure 2, three categories of urban land influence on water quality are considered, excluding recorded discharges and combined sewer overflows. Surface runoff activated pollutant sources (abbreviated as "SRA sources") include all cases in which materials are washed or eroded from land surfaces by stormwater or snowmelt. Certain other mechanisms such as sanitary sewer bypasses and scouring of catch basins and storm sewers are also included. Hydrographic modification refers to the influence of urban development on the magnitude and timing of water flows through the hydrologic system. This type of effect, which relates to water quality in several ways, is noted separately due to its strategic role in the planning approach suggested here for new development. Non-SRA pollutant sources include all other influences on water quality in urban areas, such as: sewer system leakage; unauthorized waste discharges to surface waters and storm sewers; leachate from landfills and on-site waste disposal systems; and other forms of groundwater pollution.


URBAN LAND INFLUENCES ON WATER QUALITY (Excluding Recorded Pollutant Discharges and Combined Sewers)
SURFACE RUNOFF ACTIVATED POLLUTANT SOURCES ("SRA Sources")
HYDROGRAPHIC MODIFICATION DUE TO URBAN DEVELOPMENT
NON-SRA POLLUTANT SOURCES
POLLUTANT WASHOFF FROM STREETS AND HIGHWAYS
OTHER SRA POLLUTANT SOURCES
CHANNEL AND BENTHIC CONDITIONS IN RECEIVING WATER BODIES
TRANSIENT STORM-RELATED WATER QUALITY PROBLEMS
LONG-TERM WATER QUALITY PROBLEMS (Including Problems at Extreme Low Flow)

Source: Betz Environmental Engineers, Inc.

Figure 2 ELEMENTS OF URBAN WATER QUALITY PROBLEMS

Pollutant washoff from street and highway surfaces is distinguished in Figure 2 from other SRA pollutant sources, due to the emphasis which has been placed upon the former in the literature and in discussions of urban problems generally. Channel and benthic conditions are noted because they represent a potentially critical element of water quality which may not be sufficiently acknowledged. Stream channels can be important both as a source and as a sink for stormwater pollutants. Benthic accumulations of materials also tend to form in estuaries and standing water bodies. The impacts of these accumulated pollutants, and the mechanisms whereby they are released to the overlying water, are generally not well known.

Figure 2 distinguishes between two classes of water quality problems: transient problems which occur during and immediately after storm events, and long-term problems which tend to be persistent. The former usually involve temporary dissolved oxygen depletion, and/or temporarily high concentrations of toxicants or pathogens. The seriousness of these transient problems is critically dependent upon the nature of the receiving waters affected. Long-term problems can either be the result of continuous (non-SRA) pollutant discharges, or the delayed effects of SRA loadings. Three prominent examples of long-term problems are: aquatic plant overgrowths due to nutrient enrichment; sedimentation of stream channels, rivers and harbors; and buildup of toxic materials in aquatic food chains. All of these problems can be caused by transport of particulate materials and associated pollutants during storms, as well as by continuous discharges. Two important reasons for distinguishing between transient and long-term problems in the design of management studies are that: (1) it is usually easier to evaluate the existence and seriousness of long-term problems than is true in the case of transient problems (although the linkages to unrecorded pollutant loadings are often complex and poorly understood in both cases); and (2) different types of loading estimates are required for analysis of transient and long-term problems.

An issue of immense importance in urban water quality planning is that it is often unclear just where unrecorded pollutant loadings are coming from. Commonly, washoff of materials from street surfaces is assumed to be the predominant source. This is almost certainly true in center city areas, where the only other eligible sources are sidewalks and parking lot runoff, sewer system overflows, pollutants from the atmosphere, and improper waste disposal in storm sewers. However, for the preponderance of urban land, the relative importance of specific pollutant sources tends to be uncertain. This fact has obvious implications for the ability of investigators to evaluate the benefits of selective land management controls such as streetsweeping. Studies which seek to develop loading coefficients or relationships for specific classes of urban land use may provide valuable information, but will not necessarily resolve this dilemma. For example, average loading coefficients for commercial or industrial districts may not indicate the relative pollutant contributions of streets, loading areas, sewer system overflows, unauthorized discharges, etc.; and may not distinguish between cases in which pollutant generation is widespread, versus cases in which a small proportion of establishments are largely responsible. This issue is particularly important since the customary focus of attention--street surface contaminants--may be one of the least amenable sources to control.

The second major issue has to do with the magnitude of unrecorded pollutant loadings from urban land. An extremely wide variety of loading magnitudes and stormwater pollutant concentrations have been reported in the literature. Although this question can be answered readily for a study area, once monitoring activities have been conducted, it is an important issue in the design of management studies since the anticipated loading magnitudes have an important bearing on the choice of analytical methodologies and the allocation of planning resources.

A third issue involves the general difficulty of analyzing transient water quality problems. Concentrations of toxicants and pathogens during storms may not be amenable to accurate prediction, especially when the objective is to estimate values associated with "critical conditions" having specific recurrence characteristics. Dissolved oxygen levels during dynamic flow conditions are notoriously difficult to simulate accurately, due to short-term variation in reaeration and reaction rates as well as pollutant inputs. An equally important fact is that, even if transient water chemistry is well known, it is generally hard to establish the impacts of short-term chemical phenomena on aquatic biota--which are commonly the basis for design of controls. The available literature provides relatively little assistance in conducting such an assessment, particularly with regard to the synergistic effects of multiple pollutants (e.g., high sediment, low DO, and high metals concentrations during storms). Existing water quality standards are likely not to provide adequate guidelines for design of controls, since the standards may not be relevant for transient conditions and/or may fail to cover many important water constituents. Finally, defining the appropriate critical conditions for design purposes is itself a complex problem, since stormwater impacts are related to the spatial extent of precipitation, antecedent land conditions and the intensity and duration of rainfall at a given point.

The fourth issue has to do with the overall philosophy of water quality management planning. Due to the comprehensiveness of current studies and the consideration which is given to unrecorded pollutant sources, these studies differ in a number of fundamental respects from traditional facility planning. In facility planning, the water quality problems addressed tend to be fairly well known (although this is becoming less true as a wider variety of water constituents are considered). The loadings produced by the sources under consideration can be measured directly and/or forecast with reasonable accuracy. The effectiveness of control options in limiting pollutant discharges can usually be quantified with some precision. And finally, the authority and responsibility for implementing the recommended plan usually rest with a limited number of actors who are identifiable throughout the planning process. Given these conditions, the development and selection of plans can often be based upon straightforward application of cost-effectiveness criteria, subject to environmental impact constraints. However, in the case of comprehensive areawide water quality management planning, none of the above conditions may hold to a high degree. It is therefore possible that fundamentally different criteria for development and selection of plans will be appropriate. For example, detailed comparisons of alternatives in terms of cost-effectiveness may have limited value if the effectiveness of controls is imperfectly known, and costs are to be incurred by widely different actors.

All of these issues have important implications for the selection of technical planning methodologies. In particular, they affect the planning resources which can profitably be allocated to: (1) the development of general pollutant generation relationships for urban land (with or without formal stormwater modeling); (2) the analysis of transient water quality problems, as opposed to long-term problems; and (3) the use of procedures which allow the investigator to "trade off" different control alternatives.

In order to gain some perspective on these issues, the review of urban unrecorded pollution problems has attempted to address the following questions:

1. What are the typical magnitudes of unrecorded loadings from urban areas without combined sewers?
2. What are the important sources of variation in loading rates?
3. Do loadings from new development differ from average urban pollutant yields?
4. To what extent is urban development without combined sewers likely to result in transient water quality problems?
5. What are the major factors affecting the seriousness of SRA pollutant loadings?

The findings of the review have been suggestive rather than definitive, but appear to have several important implications for water quality planning. These findings are summarized in the next section, and discussed in greater detail in Section 5 and the Technical Appendix. As a consequence of this review, an overall planning strategy has been developed, incorporating simplistic analytical procedures, which might be favorable in cases where planning resources are limited. The evaluation of planning methodologies presented in Section 6 reflects this approach, in that it points out various liabilities of methodolgies which attempt to deal in a comprehensive fashion with unrecorded loadings.

The recommended strategy distinguishes between controls applying to existing urban development and controls for new development. In the latter case, controls would be an integral part of development design, and would be specified on the basis of non-degradation principles rather than close linkages to present or projected water quality. A favorable approach might be to focus upon the water quantity effects of urban development (see Section 4). In planning activities which deal with existing water quality conditions, the highest priority would be placed on direct monitoring and analysis of problems, rather than development of generalized loading relationships. Second highest priority would be given to identification and analysis of specific sources responsible for high pollutant loadings. In both cases analysis would focus upon long-term loadings and problems unless there is a clear indication that water quality is dominated by transient effects. Land management controls which apply broadly to both existing and new urban development would be designed on the basis of general information, plus careful analysis of implementation feasibility, rather than formal cost-effectiveness analysis. Further details of this approach are presented in the next section.

SECTION 3

CONCLUSIONS

Only fragmentary data are currently available describing the contributions of unrecorded sources to water quality problems in U.S. urban areas. The present review of these data has been limited to measurements of waterborne pollutant yields from urban land areas which do not contain combined sewers or recorded effluent discharges. The most striking characteristic observed is the variability of pollutant concentrations and loadings among areas studied. The implication is that literature values of these quantities should be interpreted with extreme caution when related to any particular area.

The high loading values frequently cited in the literature may have created the general impression that urban runoff inevitably causes serious water quality problems. This conclusion could in fact turn out to be largely correct; but, the problems which are critical may not be those which have traditionally received most attention in the water quality literature. Specifically, the present review indicates that organic loadings from urban land without combined sewers are not necessarily problematic--i.e., are not necessarily sufficient to cause transient dissolved oxygen depletion. Nutrient loadings from urban and suburban areas are often no higher on a per-acre basis than loadings from agricultural land. The importance of organic and nutrient loadings from urban land must therefore be judged on a case-by-case basis. A major question mark is the role of heavy metals loadings. Although the present review suggests that there is very great variation among urban areas with regard to these loadings also, it is possible that even the cases where loadings are low could involve serious water quality problems on a long-term basis.

An important possibility, which is strongly suggested but not proven by the existing data, is that small urban basins yield greater pollutant loadings, per acre of land, than larger basins containing similar land uses. The implication is that there is a tendency for pollutants in stormwater to settle out in stream channels. On the one hand, this possibility means that pollutant loading estimates based upon small-catchment data, or upon rates of surface pollutant accumulation, may overstate the contribution of urban land to water quality problems at downstream points. On the other hand, there may be a strong need to consider potential problems created by deposited material, such as benthic oxygen demand and accumulation of toxicants in aquatic food chains. The destination of pollutants may be a very critical issue with respect to stormwater.

Relationships between pollutant loadings and watershed characteristics have been estimated statistically in the present study utilizing data for multiple urban watersheds in two geographic areas. The strongest explanatory variables for most of the water constituents studied were employment density and the percent of watershed land rendered impervious. Population density was generally not found to be an important explanatory variable, unless older housing was differentiated from new housing. A relatively low influence was attributed to the latter. This indicates that average loading values may seriously overstate the water quality impacts of new urban development. Finally, industrial land was found in two cases to constitute an influence on pollutant loadings over and above the general effects attributed to employment and impervious surfaces. The general impression created by the analysis was that unrecorded pollutant loadings tend to be more closely related to economic activity than to residential population. Exceptions would be areas in which residential neighborhoods are relatively old and/or are not served by separate sanitary sewers.

The problem of soil erosion from construction sites, and resulting sedimentation of stream channels and other water bodies, has been discussed extensively elsewhere and thus is not reviewed here in detail. A related urban problem which deserves emphasis is hydrographic modification. Construction of impervious surfaces and land drainage alterations increases the quantity of storm runoff, which in turn causes sediment production through the phenomenon of stream channel enlargement. Hydrographic modification also involves direct alteration of stream channels as part of the land development process, which disrupts aquatic habitats and increases discharge-related problems downstream. The net effects of these factors can in some instances be more serious for water use than the changes in water chemistry which accompany urban development.

With regard to unrecorded pollutant loadings generally, existing data provide little or no direct evidence regarding the typical importance of different source classes, i.e., the relative contributions of roadways, other impervious surfaces, and urban sources which do not involve impervious surfaces. There is reason to believe, however, that washoff of diffuse materials from impervious surfaces is not always the predominant source mechanism, and may not be responsible for some of the higher loadings observed. One indication is the finding, observed in the present study and elsewhere, that pollutant loading rates during storms may bear little relationship to time since the previous storm--as would be expected if progressive accumulation of materials on impervious surfaces were the primary source. (Nonlinearity of accumulation rates would explain this finding partially, but not entirely.) Another indication is that pollutant loadings tend to differ by greater amounts than would be expected if the major sources are factors which are widespread in urban areas. Groups of watersheds can be observed in which sources of street dirt such as vehicular traffic, litter, atmospheric fallout, decaying vegetation, and pet wastes should be present in roughly equal degrees, yet pollutant loadings are strikingly different.

Some of the other pollutant sources which have been found very important in particular basins are: (1) dumping of liquid and solid waste on land surfaces; (2) sanitary sewer leaks and bypasses; and (3) unauthorized discharge of liquid waste to storm sewers and receiving waters. Two critical aspects of these sources are that, first, they involve localized, site-specific conditions rather than extensive land surfaces; and second, they tend to be difficult to identify on the basis of land use or other general land data. The potential importance of pollutant sources with these characteristics is commonly recognized in the case of non-SRA sources (e.g., leachate from landfills, waste lagoons, and on-site septic systems) but frequently does not receive adequate consideration in stormwater analysis.

The available literature contains only fragmentary information for assessing the impacts of stormwater pollutant loadings on receiving water quality, particularly impacts on biologic communities. Some of the major issues are: short-term toxic effects, significance of short-term oxygen depletion, availability of nutrients in urban runoff to support algal growth, transport and deposition of particulate sources such as unauthorized discharges and sewer leakage as well as surface runoff--is not at all uniformly distributed across urban areas, even when variation in land use is taken into account. This suggests that considerable improvement could be brought about by implementing controls on a site-specific basis, once high-yield pollutant sources are identified. A reasonable strategy in many study areas may be to emphasize investigative activities that would contribute to this goal. Such activities would consist largely of field reconnaissance and chemical monitoring rather than analysis of land use patterns, since imagery and published data typically fail to capture many of the most important aspects of pollutant generation.

5. The choice of critical flow conditions for the design of controls is a significant issue in water quality management planning. For water bodies affected by SRA pollutant sources, critical conditions may be defined in terms of selected storms as well as dry-weather flows. Given the general difficulty of predicting and interpreting short-term water quality phenomena, the primary emphasis of planning studies should probably be placed upon steady-state and long-term conditions unless there are clear indications that transient problems are of major importance. In any case, the target water quality criteria for each set of critical conditions should be established directly on the basis of desired water use, and should not be dependent upon the expected levels of water quality during other critical conditions. If this principle is followed, the most stringent conditions for design of municipal and industrial treatment facilities will tend to consist of extreme low flow, in a large proportion of cases. Opportunities for trade-off between control of recorded discharges and control of unrecorded effluents will exist in these cases only to the extent that unrecorded loadings affect water quality at low flow.

6. New urban development can be handled somewhat differently than existing development in water planning studies due to the opportunities which

exist for incorporating control measures in development design, and due to the relative ease of establishing private responsibility for pollutant reduction. A feasible planning approach in many instances is to treat new development as a wholly or partly independent problem, and to design controls on the basis of uniform non-degradation principles rather than on predicted levels of water quality. As discussed in the next section, a helpful strategy may be to focus largely on the problem of hydrographic modification.

Various aspects of this general approach are discussed further in Section 7, following the examination of empirical data in Section 5 and the evaluation of specific planning methodologies in Section 6.

SECTION 4

RECOMMENDATIONS

The specific planning methodologies recommended here deal primarily with new urban development, but are also relevant in some instances to existing development. Perhaps the most significant element of these methodologies is the selection of problems to be addressed. The position taken here, which has been based in part on review of empirical data, is that the water quality impacts of completed urban development with sanitary sewerage can be controlled adequately in most instances by focusing upon the problem of hydrographic modification. That is, preventive measures dealing with water *quantity* will ordinarily prove to be adequate controls for water *quality*, assuming that reasonably high standards of public cleanliness can be maintained. The types of problems and associated control measures which have been selected for emphasis are thus the following.

1. *Control of erosion from construction sites*. Considerable experience already exists in the design and application of erosion/sedimentation control measures. These measures should deal with hydrographic modification--i.e., increased runoff--caused by construction activity as well as with soil loss *per se*. Thus, some form of runoff detention *should* be included, along with other physical controls. An overall approach for quantitative evaluation of erosion/sedimentation controls is outlined here in Section 11.

2. *Control of the location, design, and operation of on-site sewage disposal systems*. On-lot waste disposal systems, particularly domestic systems, constitute a very serious water quality problem in many areas. Control of these facilities has been oriented primarily toward prevention of nuisances and health hazards, rather than protection of water quality. Implementation of measures needed to achieve adequate groundwater and surface water quality may therefore require redefinition of existing regulatory functions, with or without additional enabling legislation. The controls

implemented should include the following: (1) prevention of new on-site disposal systems in areas where soil characteristics, land slope, or proximity to receiving waters will preclude satisfactory operation; (2) design of new systems in order to assure adequate performance under the given land conditions; and (3) maintenance of performance standards for septic system operation. Prohibitive soil characteristics for new on-site systems could include overly rapid percolation, which would result in groundwater pollution, as well as overly slow percolation. Maintenance of performance standards may require significant intensification of monitoring activities relative to present practices, which typically are limited to investigation of nuisances reported by residents.

3. Construction of leakproof, accessible sanitary sewers. Sanitary sewer leakage and bypasses contribute significantly to water problems in many areas. Therefore, in the construction of new systems, best available technology should be utilized wherever possible. Leakproof sewers are now technically feasible, if manufacturers' specifications are followed closely. Although extra construction and monitoring costs are likely to be involved, these costs would appear to represent a very wise investment on the part of a community. For some types of development, the most cost-effective strategy for water quality control could conceivably involve combined sewers; but separate storm and sanitary sewers will be assumed here. An important objective in such cases is to keep the systems as separate as possible. Roof drains, foundation drains, and other sources of water for which treatment is unnecessary should never be connected with sanitary sewers, since this inflates waste treatment costs and may lead to overload of the system and creation of bypasses. Conversely, new development should be designed so as to discourage the use of storm sewers for disposal of wastes requiring treatment. Finally, a very important objective is to design new development in such a way that sanitary sewers are readily accessible for repairs. A favorable design may involve location of sewers beneath

sidewalks or grass strips bordering the roadway, rather than under the roadway itself.

4. Control of hydrographic modification. The control of hydrographic modification due to urban development involves three aspects: (1) prevention of increase in peak discharge; (2) prevention of decrease in the base flow of streams and the rates of aquifer recharge; and (3) protection of water courses from encroachment and alteration. Controls dealing with hydrographic modification should be designed to maintain existing conditions as closely as possible; zero impact is in most cases a feasible goal. With regard to the first two objectives just listed, the most cost-effective design for a given development project is likely to involve a combination of control measures. Runoff detention devices are generally needed to prevent increase in peak discharge, whereas base flow maintenance and aquifer recharge may require infiltration devices (with careful attention paid to possible groundwater pollution due to these devices). Overall modifications of development design, such as restriction of impervious coverage, can be extremely useful, but rarely are sufficient *per se* to attain zero impact.

A critical aspect of focusing upon hydrographic modification is that the controls utilized will have very substantial water *quality* benefits. Temporary storage of storm runoff in detention basins brings about significant reductions in most pollutant loadings, due to settling out of particulate materials. Infiltration devices tend to achieve much greater pollutant reductions. For most types of new urban development, it is felt that the decrease in pollutant loadings thus achieved by control of hydrographic modification is likely to be sufficient for water quality protection--assuming that other measures as specified below are also implemented.

The use of water quantity as an explicit basis for design and defense of water resources protection measures has a number of distinct advantages, given the present level of knowledge concerning unrecorded pollution. The problems created by hydrographic modification, which include increased flooding as well as channel disturbance and sediment yield, are directly observable and intuitively understandable to the layman. The feasibility of zero impact with regard to water quantity effects means that appropriate design parameters for control devices can be established unambiguously, through reference to existing conditions. Implementation of controls can be accomplished by adoption of performance standards, which allow some freedom of adjustment, or alternatively by requiring specific control measures on an areawide or site-specific basis. The performance of controls once in place is relatively easy to monitor. Finally, considerable experience already exists in many communities regarding various aspects of runoff control.

A fact which has considerable practical significance is that control of hydrographic modification does not necessarily require land use control, since mitigative measures can be utilized at almost any buidable site. The direct and indirect costs of providing these measures, which are usually borne by private builders, tend to be small relative to total project cost. Thus, prevention of hydrographic modification will not prohibit most types of development at most locations. Regardless of the need for land use control in U.S. communities, it is felt that most water resources protection measures developed in current planning programs should not be closely identified with land use control, since such an identification might limit implementation to a relatively few areas. The major exceptions would be measures dealing with location and construction of new on-site septic systems, which might involve a substantial degree of _de facto_ land use control.

It is anticipated that runoff control for a large proportion of new development projects will involve the use of stormwater detention facilities. This fact is important to the overall strategy recommended here. As knowledge is gained regarding the water quality impacts of urban runoff, it could eventually be established that chemical treatment of stormwater is generally needed. If so, the availability of runoff detention facilities will place a community in a favorable position for implementation of additional controls, since the very high costs of providing runoff storage capacity in existing developed areas will be at least partially avoided.

Some other comments regarding stormwater detention facilities are the following. First, impoundments constructed for runoff detention should be designed so that there is virtually zero chance of structural failure. Second, care must be taken to see that nuisances are not created by these facilities, such as insect problems and safety hazards. Third, some degree of maintenance is required for all runoff control devices. In the case of stormwater detention facilities, it is essential that outlets be kept clear and that accumulated sediment be removed periodically. The material which is removed can be utilized as fill in construction projects, preferably at locations where it is not in contact with surface waters or groundwater. Various aspects of the design of detention facilities are discussed in detail in Section 9.

Protection of stream channels and other water bodies from direct physical alteration is considered a very important element of the approach suggested here. The objectives include not only preservation of aquatic habitats, and retention of the natural capacity of stream channels to dissipate flooding effects (i.e., to reduce flooding downstream through temporary storage of stormwaters), but also protection of the role of headwater stream channels as "sinks" for sediment and other pollutants. As indicated elsewhere, this role of stream channels may be very significant. Although accumulations of pollutants are generally undesirable at any location, it is probably better for such materials to be deposited in headwater alluvial sediments than to affect ambient water quality at downstream points where water use is generally most intensive. A number of issues involving protection of watercourses (including the question of how to define the surface water system subject to protection) are discussed in Section 9. An important point is that efforts in this regard should be coordinated, where possible, with ongoing or prospective flood plain management programs.

The planning methodologies and control alternatives emphasized here have been chosen because of their relevance specifically to new urban development. The present discussion should not be interpreted to mean that other measures, which could be applied to both existing and new development, are not necessary. The success of the approach suggested here is in fact dependent upon the assumption that land conditions and waste management practices can be maintained at levels which are presently above average relative to U.S. urban areas generally. Thus, adequate control of the water quality impacts of newly-developed land will require at least three classes of actions other than those discussed extensively here, namely: (1) "housekeeping" measures, such as routine cleaning of streets, parking lots, catch basins, and other areas where pollutants accumulate; (2) public information programs to create awareness of water quality problems and their causes; and (3) actions to prevent the occurrence of site-specific pollutant sources. The last element could include monitoring of a wide variety of waste management practices and facilities. A potentially promising area of action, which could be included as a fifth control category in the list presented above, is waste management planning for new development projects which are expected to constitute especially high-yield pollutant sources. Possible examples are establishments engaged in petroleum distribution and sales, and certain types of manufacturing operations. An objective would be to make waste generation and waste management practices subject to review by local planning agencies in a fashion similar to other aspects of development design. The outcome could consist of design modifications, operating agreements, or special water quality control devices, as needed to prevent impacts on a site-specific basis.

A general review of planning methodologies for water quality control is presented in Section 6. Sections 7 and 8 outline overall strategies for dealing with existing and new urban development in current planning efforts, with emphasis in the latter case upon the mechanisms which can be utilized to implement control measures. The specific planning methodologies selected for emphasis are presented in Sections 9, 10, and 11. Extensive discussion of underlying technical issues in water planning, particularly the response of receiving waters to pollutant loads, is contained in the Technical Appendix to this volume.

SECTION 5

POLLUTANT GENERATION

Introduction

The present study has included a rather extensive review and analysis of existing data pertaining to unrecorded pollutant sources in urban areas. The scope of this review has been limited to urban land influences on water quality other than recorded effluent discharges (i.e., municipal and industrial effluents) and combined sewer overflows. Agriculture, which is occasionally found within urbanized areas, is not discussed. These restrictions have been considered necessary in order to concentrate upon the factors most relevant to the impacts of new urban development. The objective of the review and analysis has been to consider the following questions, as posed in the summary section:

1. What are the typical magnitudes of unrecorded pollutant loadings from urban areas without combined sewers?

2. To what extent does variation exist in these loadings; and what are the important sources of variation?

3. Is washoff of diffuse materials from streets and other impervious surfaces usually the predominant source of unrecorded pollution?

4. Do loadings from new urban development differ systematically from average urban loadings?

5. To what extent is urban development, with separate sewers, likely to result in transient water quality problems?

For a variety of reasons, it has been impossible to obtain definitive answers to any of these questions; and some have been addressed only by inference. The present section contains a somewhat abbreviated discussion of the findings, emphasizing the materials which have greatest relevance for design of water planning studies. Additional description is contained in the Technical Appendix to this volume, which deals at length with the empirical land-water relationships estimated as part of this study.

Literature discussion of unrecorded pollution problems in urban areas has focused primarily upon stormwater pollution, i.e., upon surface runoff activated (SRA) pollutant sources. Aside from combined sewer overflows, two classes of SRA pollutant sources have typically received primary attention: soil erosion from construction sites, and washoff of dirt and dust from impervious surfaces, particularly streets. The potential importance of soil erosion caused by construction activity, and the need for control of this problem, has been well established in the literature (although sediment loading magnitudes and water quality impacts tend to be difficult to predict in individual cases).

With regard to urban sources other than construction activity, perhaps the most extensive body of empirical research available deals with rates of pollutant deposition and accumulation on street surfaces. The present review has not dealt at length with this information, however, but instead has focused upon observed loadings of waterborne pollutants at in-stream locations. The reasons for this approach, other than a desire to avoid redundancy with existing publications, are that: (1) major questions exist regarding the manner in which dirt and dust accumulation on land surfaces relates to in-stream pollutant loadings and water quality conditions; and (2) accumulation of materials on impervious surfaces is not the only urban SRA pollutant source (notwithstanding combined sewers).

The loading data under discussion pertain only to stream points and storm sewer outfalls which are unaffected by recorded effluent discharges, combined sewers, or agricultural land. Much of the information utilized has been derived from the following sources, each of which contains data for multiple urban watersheds.

1. An ongoing program conducted jointly by the U.S. Geological Survey and the City of Philadelphia has involved monthly sampling of numerous watersheds in and near Philadelphia since 1970 (see Radziul, et al, 1975). Many of these watersheds were chosen explicitly on the basis of land use; thus,

the network provides a good representation of suburban and urban land in the Philadelphia area (excluding heavy industrial land and urban core areas). Data for ten of these basins, ranging in size from 1 to 21 square miles, have been utilized in the present study.

2. Storm runoff from 15 small basins in Tulsa, Oklahoma, was analyzed intensively in a study by AVCO Corporation (AVCO, 1970). The basins ranged from 64 acres to 938 acres in size, and provided very good coverage of the residential, commercial, and industrial land uses typically found in a medium-sized urban area.

3. Numerous suburban watersheds in Montgomery County, Maryland, were monitored in a study which was concerned primarily with biologic effects of urban runoff (Ragan and Dietemann, 1975). This study yielded only limited chemical data but contained very important implications for urban land impact.

Further discussion of these and other data sources is contained in the Technical Appendix.

Variability of Pollutant Loadings

The most striking overall feature of observed pollutant concentrations and loadings is the variability of values among study areas. This characteristic is illustrated here for organic pollutants in Table 1 and for heavy metals in Table 2.

Average BOD concentrations in storm runoff from urban basins range from about 3 mg/l to upwards of 30 mg/l, as shown in the second column of Table 1. Annual loadings, in pounds per acre of watershed area, may vary to a lesser extent than concentrations, although Table 1 is somewhat deceptive in this regard since annual loadings are unavailable for several of the basins with high average concentrations. A similar situation prevails in the case of COD, for which average concentrations range from about 20 to well over 100.

Literature discussions of organic loadings in urban storm runoff have referred primarily to the higher BOD and COD concentrations shown in Table 1, such as the values for Des

TABLE 1

ORGANIC POLLUTANT LOADINGS FROM URBAN AREAS WITH SEPARATE SANITARY SEWERS

		BOD			COD		
	Population Density (persons/acre)	Mean Concentration (mg/l) Wet Conditions	Mean Concentration (mg/l) Dry Conditions	Annual Loading (pounds/acre/yr.)	Mean Concentration (mg/l) Wet Conditions	Mean Concentration (mg/l) Dry Conditions	Annual Loading (pounds/acre/yr.)
Basins Less Than 2 Square Miles							
Des Moines, Iowa[1] (4 areas)	---	36	---	---	---	---	---
Washington, DC[2]	38	19	---	---	335	---	---
Cincinnati, Ohio[3,4]	8.9	19	---	53	99	---	347
Durham, NC[5]	9.5	---	---	84	---	---	---
Durham, NC[6]	6.0	75-90*	15	---	170	29	---
Tulsa, OK[7] (8 residential basins)	9.3	12	---	23	87	---	171
Tulsa, OK[7] (7 non-residential basins)	2.6	12	---	31	101	---	234
Philadelphia, PA, Area (3 basins)	15	5.3	2.3	22	24	10	115
New Jersey[8] (2 basins)	4.8	3.1	0.8	15	---	---	---
Basins 2 to 10 Sq. Mi.							
Castro Valley, CA[9]	11	14	---	---	---	---	---
Ann Arbor, MI[10]	---	28	---	---	---	---	---
Philadelphia, PA, Area (4 basins)	7.0	5.0	3.8	24	25	14	127
Bull Run, VA[12]	7.5	8.5	2.5	21	---	---	---
Basins More than 10 Sq. Mi.							
Philadelphia, PA, Area (2 basins)	8.0	4.4	2.8	19	24	11	112
Montgomery Co., MD[11] (19 stations in 6 bsns.)	2-12	1.8		15*	---	---	---

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* Estimated

References:
1. Henningson, 1973
2. Weston, 1970
3. Weibel, 1969
4. Weibel, 1964
5. Bryan, 1970
6. Colston, 1974
7. AVCO, 1970
8. Whipple, *et al*, 1974
9. Hydrologic Engineering, 1972
10. Burm, 1968
11. Ragan, 1975
12. Randall, 1975

Moines, Washington, Cincinnati, Durham, and Ann Arbor. As a result, urban runoff has frequently been compared unfavorably to secondary sewage effluent in terms of strength. However, the data included in Table 1 for basins in Pennsylvania, New Jersey, and Maryland indicate that concentrations of organic material in urban runoff are not necessarily high relative to sewage effluent or other standards of comparison. Available data also suggest that these organic loadings do not necessarily create dissolved oxygen problems. For the 10 Pennsylvania basins, in which dissolved oxygen has been sampled along with BOD and other water constituents, only three instances have been observed in which DO was below 7.0 mg/l during a storm period. (The dissolved oxygen standard applying to these streams is 4.0 mg/l.) Similarly, for the Montgomery County, Maryland basins, the mean of minimum DO values observed at the 19 stations draining urbanized areas was 7.1 (Ragan and Dietemann, 1975, p. 58). The comparable figure for basins with no urban development was 6.9 mg/l. On the other hand, organic loadings have been shown to affect dissolved oxygen in the Castro Valley, California, basin (Lager and Smith, 1974, p. 81) and would be expected to have this result in cases where BOD concentrations are as high as in Des Moines, Durham, and Ann Arbor.

The loading variation shown in Table 1 can be explained in part by several circumstances. As indicated in the first column of the table, the Washington, D.C., data pertain to a densely urbanized basin (containing 38 persons per acre, or 24,000 persons per square mile), which would not be generally representative of urban land outside the core areas of major cities. The Durham, North Carolina, data obtained by Colston (1974)--which have been much publicized in the literature--pertain largely to a slum area which is characterized by dilapidated housing, a total lack of storm sewerage, numerous unpaved streets, and extremely poor environmental conditions in terms of trash and garbage accumulation. The Durham data thus may be important in demonstrating extreme conditions, but do not appear to be generally relevant for urban areas in the U.S.

A factor which could be important for a wide variety of pollutants is the possibility that loadings are systematically higher in small, totally-sewered catchments than at downstream points in natural channels. This possibility was raised by Ragan and Dietmann in attempting to explain the relatively low BOD concentrations observed in Montgomery County (1975, p. 61):

> "Many of the studies reporting high BOD's in urban storm water runoff have been conducted in very small watersheds. Most of the watersheds in the present study were in excess of ten square miles. It is probable that the mechanism of BOD transport is similar to that of sediment transport and, therefore, the role of watershed size must be considered ..."

Constituent losses during transport would involve settling of particulate material and associated pollutants in natural channels. This factor would explain somewhat the figures shown in Table 1, which have been arranged according to watershed size. It is relevant that the 5-square-mile Ann Arbor basin, in which relatively high BOD concentrations were observed, was totally storm-sewered, so that losses of material during transport would presumably be minimal.

Variation in pollutant loadings from urban land is also related to the types of land development and activity present, as might be expected. The relationships which have been estimated as part of the present study are summarized in the next sub-section.

Relatively less information is available for other pollutants besides organics for urban basins such as considered here. Table 2 presents a comparison of average heavy metal concentrations observed in four areas. In this case, the most striking variation is between the concentrations observed in the ten Pennsylvania basins and the much higher concentrations observed in other areas. For each of the metals considered, the average Pennsylvania concentration is lower than all other concentrations by a factor of between 3 and 25. These differences could be explained partially by the special characteristics of the Durham basin mentioned earlier, and by the phenomenon of pollutant losses during transport (which would affect the Pennsylvania basins but not the New York or Lodi basins). Land use intensity is probably also a factor. In any case, the differences are significant in view of the fact that the Pennsylvania basins are considered to be broadly representative of much of the urban and suburban land presently found in the U.S. (Further discussion of heavy metals is presented below and in the Technical Appendix.)

The purpose of this discussion has been simply to indicate that data from the literature should be interpreted with considerable caution, and generally cannot be used to infer the seriousness of problems in a particular area.

TABLE 2

COMPARISON OF AVERAGE HEAVY METAL CONCENTRATIONS IN URBAN STORM RUNOFF (mg/l)

Metal	Location			
	Durham North Carolina[1]	New York New York[2]	Lodi New Jersy[3]	Philadelphia Pennsylvania[4]
Lead	0.46	---	0.90	0.035
Zinc	0.36	1.6	0.62	0.12
Copper	0.15	0.46	0.15	0.003
Chromium	0.23	0.16	0.03	0.01
Nickel	0.15	0.15	0.08	0.019

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[1] Colston, 1974.

[2] Klein, *et al*, 1974.

[3] Wilber & Hunter, 1975.

[4] Average for 10 basins (wet days); see text and Technical Appendix.

Relationships between Pollutant Loadings and Watershed Characteristics

Use of formal statistical methods to estimate relationships between pollutant loadings and watershed characteristics has been limited in the present study by the fragmentary data available and the need to control influences due to geographic location. The sample cases chosen for analysis consisted of the 10 Pennsylvania basins and 13 of the 15 Oklahoma basins mentioned previously in this Section, plus 3 watersheds in New Jersey (Whipple, et al, 1974). The quantities analyzed were the annual loadings of various water constituents in pounds per acre per year. The specific constituents were: BOD, COD, total organic carbon, suspended solids, organic Kjeldahl nitrogen, ammonia, nitrate, soluble orthophosphate, and total phosphate. The watershed characteristics utilized as explanatory variables in the analysis were the following:

P1 - Population density in persons per acre

P2 - Density of population in dwellings constructed before 1940, in persons per acre

P3 - Density of population in dwellings constructed after 1940, in persons per acre

M - Median family income (as reported in 1970 Census for the year 1969)

E - Employment density in persons per acre

I - Impervious surface as percent of watershed area

All of the density measures were gross rather than net density, i.e., consisted of population or employment divided by the acreage of the entire watershed. Due to problems of data availability, areal measurements of land use were not utilized in the analysis, except as a basis for forming subsamples of watersheds. Given the constraints of the analysis and the results obtained, it is felt that further consideration of land use variables would not have added significantly to the explanation of loadings. (Further discussion of the form of the analysis and the derivation of variables is contained in the Technical Appendix.) The analysis involved simple and multiple regressions in which dependent variables expressing pollutant loadings were related to the above factors as independent variables.

The findings of the analysis can be summarized as follows. Strong relationships with watershed characteristics were identified for almost all of the chemical loadings analyzed. The best explanatory variable in almost all cases was employment density. Percent imperviousness, which includes the effects of both residential and non-residential land uses, was also statistically significant in explaining the observed loadings of a majority of constituents. Population density was generally not found to be a good predictor of pollutant loadings, except when residential basins were segregated and separate consideration was given to population in pre-1940 housing. The effects then attributed to pre-1940 housing were much greater than the loadings attributed to population in post-1940 housing. In the case of nitrate, loadings were shown to be highly sensitive to the presence of dwellings with on-site sewage disposal (utilizing data from another study by the present author). Finally, in two cases, the existence of industrial development was found to be highly significant, over and above the general importance attributed to employment and imperviousness.

The relationships obtained, which pertain largely to employment density and percent of impervious land, are presented numerically and graphically in the Technical Appendix. Overall, the results for different water constituents are found to be remarkably consistent. On the basis of various conversion factors, the equations appear to indicate that each additional employee in an urban watershed increases pollutant yields by roughly four times as much as each additional resident. The predominant cause of unrecorded pollutants in urban areas would thus be economic activity rather than population (although these two factors are, of course, inseparable for an urban area as a whole). This finding may have been influenced, however, by the fact that the sample watersheds studied here contained a somewhat higher proportion of new residential development than would be generally true for the U.S.

The importance of age of residential development as an explanatory factor is considered highly significant. Differences between the pollutant yields from new and old development may be due to associations between age of housing and various socioeconomic characteristics, which are in turn correlated with factors directly affecting pollutant generation. Some other possibilities are: physical deterioration of streets and buildings; correlations with air quality; and especially, the condition of sanitary sewer systems. In any case, an important implication is that loading estimates obtained from the literature or from monitoring of existing urban land may systematically overstate the water quality impacts of new urban development. A significant unanswered question is whether the loading differences between new and old development are due strictly to former construction practices, or whether the loadings from new development can be expected to increase progressively over time.

Although the estimated equations were reasonably accurate in predicting pollutant loadings for the sample basins studied, the extent of variation among land areas which is implied by these relationships is not sufficient to explain the differences which exist between loading values reported in the literature. This circumstance is thought to reflect the extent to which pollutant generation is not systematically related to overall characteristics of urban land. As is discussed below, a significant proportion of pollutant loadings produced during both storm and nonstorm periods may involve localized site-specific sources which cannot be identified readily through land use analysis.

Nutrients

Urban land is frequently cited as an important source of nutrients, due to factors such as lawn fertilizer application, atmospheric fallout, domestic animals, erosion from construction sites, and sewer leakage. In order to provide some perspective on this problem, Table 3 presents areal loadings of nitrogen and phosphorus, as N and P, obtained from the literature and from other sources cited earlier. The available data for urban basins with separate sanitary sewer systems are fragmentary but fairly consistent. Loadings of total Kjeldahl nitrogen (ammonia plus organic nitrogen) range between perhaps 1 and 5 pounds per acre per year. For both organic nitrogen and ammonia, loadings from commercial and industrial areas appear to be higher on the average than loadings from residential areas. Nitrate yields, as N, typically range between 5 and 15 pounds per acre per year. An important fact not illustrated in Table 3 is that nitrate yields may be extremely sensitive to the presence of on-site septic systems (Howard and Hammer, 1973; see also the Technical Appendix).

TABLE 3

NUTRIENT LOADINGS IN POUNDS/ACRE/YEAR

	Nitrogen					Phosphorus	
	OKN	NH_3-N	TKN	NO_3-N	Total N	Soluble OPO_4-P	Total P
URBAN LAND							
Cincinnati, Ohio[1]					9.9		
Ann Arbor, MI[1]			1.3			0.3	1.1
Washington, DC[2]					16.7		1.8
Roanoke Basin, VA[3]							4.8
Rock Creek, DC/Maryland[1]			3.2	13.5			1.8
Philadelphia Area (6 residential basins)		2.2		11.8			1.1
Philadelphia Area (3 non-residential basins)		2.8		7.0			1.3
Tulsa, OK (8 residential basins)	1.5					0.6	
Tulsa, OK (7 non-residential basins)	2.4					1.0	
Typical Urban Loadings*					10-20		1-2
SECONDARY MUNICIPAL EFFLUENT**		25-35		5	35-40		10-17
AGRICULTURAL LAND							
Brandywine Creek, PA[4]				5			0.6
Agricultural Basins[3]		0.4		3			0.15-0.35
Cropland, U.S.[1]					0.1-14		0.07-3.3
Feedlot Runoff[1]					100-1800		10-3.3

Notes: *Figures apply to medium-density urban development with sanitary sewers in reasonably good condition.

**Loading rates due to municipal discharge assume 7 persons per acre and 100 gpd wastewater generation.

References: (1) Loehr, 1974 (2) Jaworski, 1970 (3) Gizzard & Henelle, 1972
(4) Coughlin & Hammer, 1973

Loadings of soluble orthophosphate, as P, from completed urban development are typically between 0 and 1.5 lb/acre/year; and total phosphorus is usually less than 2 lb/acre/year unless there is construction activity or sanitary sewer leakage. More than perhaps any other water quality parameter, phosphorus loadings are sensitive to the type and condition of sewerage facilities (believed to be the factor responsible for the high loading observed in the Roanoke Basin). If sewers are tight and no major industrial sources are present, phosphorus concentrations in streams draining urban land can be less than 0.3 mg/l during both wet and dry weather. The other critical factor is the existence of construction activity, which can result in very high phosphorus loadings. In contrast to nitrate, on-site sewage disposal may not be a major source of phosphate in areas where soils are favorable (Howard and Hammer, 1973).

Loadings of 10 to 20 lb/acre/year for nitrogen and 1 to 2 lb/acre/year for phosphorus are cited in Table 3 as typical for medium-density urban development with sanitary sewers in reasonably good condition. These figures are contrasted with nutrient loadings due to secondary municipal effluent, which assume a gross population density of 7 persons per acre (substantially lower than the density for many of the urban basins considered). A significant fact is that loadings of phosphorus and ammonia nitrogen due to municipal effluent can exceed the loadings due to land drainage by a factor of 10. The purpose of this comparison is simply to indicate that sewer system maintenance and strict control of construction activity may be adequate for control of nutrients from urban land, even in cases where problems of nutrient enrichment require advanced treatment of recorded effluents.

Comparisons with nutrient yields from agricultural land, shown in the lower portion of Table 3, are also instructive. As an example, rural land in the Brandywine Basin--of which only about 50% is intensively used for agriculture--yields about 5 pounds per acre per year of nitrate nitrogen, and 0.6 lb/acre/year of phosphorus. Thus, the nutrient yields from agricultural land per acre can be on the same order of magnitude as loadings from urban land. These figures suggest that in watersheds containing large agricultural regions, the nutrient yields from completed urban development with separate sanitary sewerage may not be a major issue.

Heavy Metals

Over the past few years there has been an increasing interest in the contamination of receiving waters with heavy metals such as mercury, lead, cadmium, chromium, and zinc, due to their potentially high toxicity. A particularly significant fact is that heavy metals are non-degradable and hence persist in the environment for extended periods of time. In addition, heavy metals tend to precipitate out of solutions with relatively neutral pH values and some alkalinity; and they may be adsorbed on clay particles or bound by such compounds as the hydrous oxides of iron and manganese. As a result, these materials are concentrated in the solid phases of water systems. Even though the water itself may contain only small amounts of these materials, the particulate matter in the water, and especially the benthic deposits, may contain considerable quantities.

Because metals are conservative they may undergo biological magnification in the food chain, reaching concentrations in the upper trophic levels several orders of magnitude greater than those which originally existed in the water. Finally, depending on specific environmental conditions, certain metals such as mercury may undergo microbiological transformations to forms exhibiting significantly more toxicity than original forms.

Heavy metals are known to enter receiving waters from a variety of sources; but little information is available regarding the typical loadings of these materials in urban stormwater. The variability of heavy metals concentrations among urban areas has already been suggested in Table 2. The heavy metals data for the abovementioned Philadelphia area watersheds (which are presented in detail in the Technical Appendix) are considered particularly significant, since they are among the few existing examples of information describing in-stream metals loadings due entirely to urban unrecorded sources--in this case largely non-industrial sources. As noted earlier, the metals concentrations observed in the ten Philadelphia area basins are relatively low. For example, the average lead concentrations for all basins during both wet and dry conditions are below 0.05 mg/l; and less than 10% of observed values exceed 0.1 mg/l. In contrast, the lead concentrations reported in other studies and computed by indirect methods may exceed 0.5 mg/l (see Table 2). This discrepancy could be indicative of a strong tendency for heavy metals to settle out in stream channels rather than passing through.

TABLE 4

SUMMARY OF HEAVY METAL DATA FROM PHILADELPHIA WATERSHEDS

Station	Number of Metals for Which Criteria were Violated (1)			
	Dry Weather		Wet Weather	
	Max	Avg	Max	Avg
1	6	4	5	4
2	6	3	4	4
3	5	3	5	4
4	6	3	3	3
5	5	2	8	4
6	7	2	6	3
7	6	3	5	3
8	6	2	5	3
9	6	1	6	3
10	4	4	4	3
Total	57	27	51	34

Metal	Number of Stations at Which Criteria were Violated (1)			
	Dry Weather		Wet Weather	
	Max	Avg	Max	Avg
Cadmium (Cd) (2)	6	0	5	2
Chromium (Cr)	5	1	2	0
Copper (Cu) (2)	10	1	8	0
Iron (Fe)	10	5	10	10
Lead (Pb) (2)	6	1	5	2
Manganese (Mn)	10	9	10	9
Nickel (Ni) (2)	0	0	1	1
Silver (Ag)	0	0	0	0
Zinc (Zn) (2)	10	10	10	10
Total	57	27	51	34

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(1) Maximum permissible concentration based upon most stringent freshwater criteria set by EPA's "Draft Quality Criteria for Water," October 1975.

(2) Most stringent criterion based upon toxicity to freshwater aquatic life.

In any case, it appears possible that the contributions of ubiquitous urban factors such as traffic and litter to in-stream heavy metal concentrations may actually be fairly low, and that high concentrations tend to reflect site-specific factors, to perhaps a greater extent than is true for other water pollutants. As an example, the Philadelphia area watersheds as a whole contain more than 50 square miles of land and over 300,000 people; yet well over a third of the total lead yield appears to be coming from a single 5-square-mile basin containing less than 20,000 people. Another interesting aspect of the Philadelphia data is that average wet-weather concentrations fail to exceed average dry-weather concentrations for a large proportion of the metals monitored. A similar finding was observed in Durham (Colston, 1974). Non-SRA pollutant sources are usually not mentioned in connection with heavy metals, but may be responsible for a significant proportion of total in-stream loadings.

Relatively little definitive knowledge exists concerning the long-term impacts of heavy metals on aquatic biota; and even less is known about the possible shockloading effects of temporarily high metals concentrations. A very important point, however, is that even ambient concentrations on the order observed in the Philadelphia basins may be serious. In Table 4, these concentrations are related to the criteria proposed by EPA for protection of agricultural water use, aquatic life, and public water supply. The most stringent criterion for each metal, expressed as a maximum concentration, has been selected; and violation of this criterion by either the maximum or the average concentration for a given basin (station) has been noted. Table 4 tabulates the number of metals for which each station is in violation, and the number of stations in violation for each metal. It is found that maximum concentrations violate the most stringent criteria in about 60% of possible cases, and that average concentrations violate criteria in 30% to 40% of possible cases, for both wet and dry conditions. As shown in the right-hand side of the table, the preponderance of violations occur for iron, manganese, and zinc, plus copper in the case of violations by maximum concentrations. The most stringent criteria for iron and manganese are based on public water supply, whereas the zinc and copper violations are related to aquatic life.

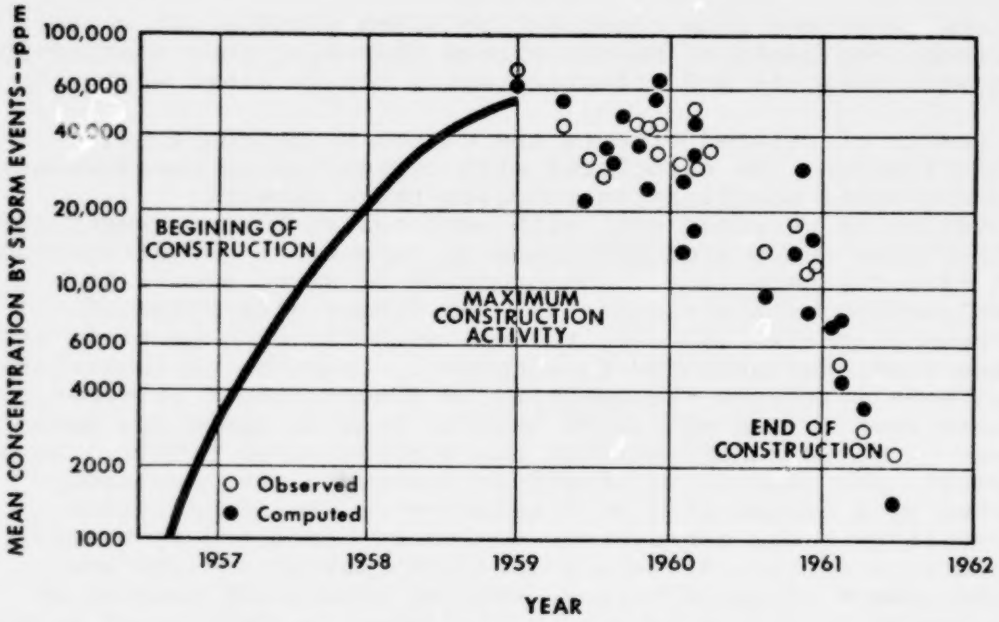
Finally, the significance of heavy metal buildup in stream channels and other benthic deposits is not well known, due in part to lack of knowledge regarding the recycling processes which affect bottom sediments generally. This aspect of the heavy metals problem could well prove to be the most serious, especially in cases such as the Philadelphia basins where ambient concentrations are generally low.

Sediment and Hydrographic Modification

Sediment loadings in stormwater occur due to detachment and transport of soil particles from earth surfaces, including gullies and stream channels, and washing of particulate matter from impervious surfaces. The rate at which sediment is yielded from an earth surface is highly dependent upon transient hydrologic conditions and upon the specific nature of the surface. In addition, the loading produced at any downstream point is governed by complex transport processes.

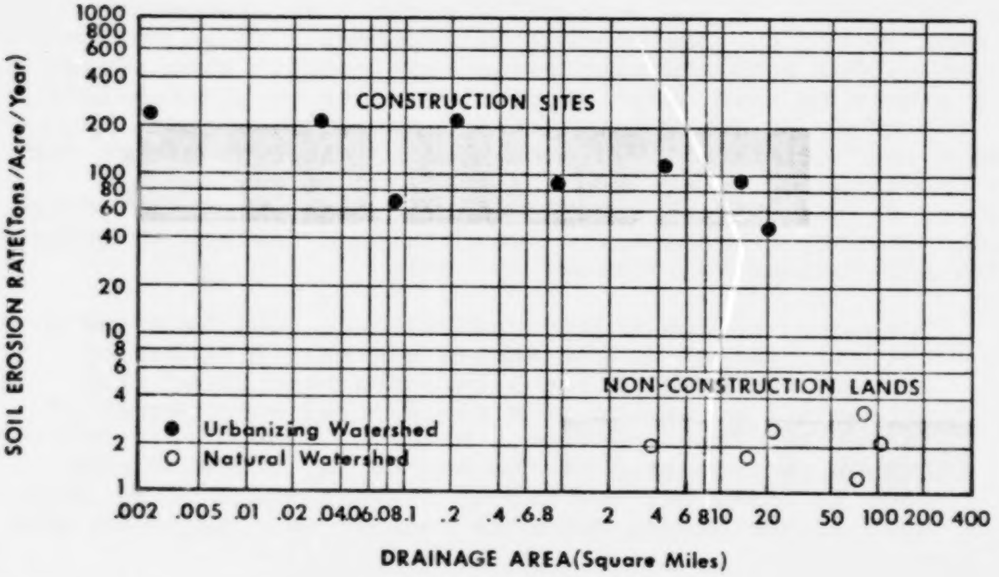
The problems caused by sediment loadings involve three factors: (1) the role of particulate matter as a medium for transport of chemical pollutants in storm runoff; (2) the direct impacts of suspended solids *per se* upon water use; and (3) the impacts produced by settling of particulate material in stream channels, impoundments, and other water bodies. The first of these factors tends to be of greatest importance for particulate materials yielded by impervious surfaces and other stable urban land, since the quantity of these solids is generally less critical than their chemical composition. The most significant sources of bulk sediment in many urban areas are construction activity and erosion of watercourses due to hydrographic modification.

Sediment from construction sites is a widely recognized problem which has already been addressed by legislation in a number of states. The magnitude of erosion which can occur as a result of exposure and disturbance of the land in construction sites is extremely great. Without control measures, the loading rate of suspended solids during construction can be from 10 to 100 times as great on a per-acre basis as the loading rate from the land before development. Figure 3 shows the pattern of sediment yields which occurred during development of a 58-acre basin in suburban Maryland. Figure 4 compares the sediment yields observed in a number of urbanizing watersheds in Maryland and Virginia with data for nearby rural basins. Typically, much of the material



Source: Guy, H.P. U.S. Department of Agriculture
Misc. Pub. 970, 1963

Figure 3 SEDIMENT CONCENTRATION IN RUNOFF FROM AN URBANIZING BASIN IN MARYLAND 1957-1962



Source: American Society of Civil Engineers,
"Urban Runoff Quantity & Quality,"
Wm. Whipple, ed., August 1974

Figure 4 SEDIMENT YIELDS FROM CONSTRUCTION SITES AND NON-CONSTRUCTION LANDS IN MARYLAND AND VIRGINIA

which is eroded from construction sites settles out on the bottoms and banks of nearby stream channels, thus destroying aquatic habitats and affecting water use in other ways.

A number of related effects are caused by hydrographic modification. As associated with typical urban development, hydrographic modification involves three aspects: (1) covering of pervious soil with surfaces such as pavement and structures which are impervious to rainwater; (2) alteration of land drainage (e.g., construction of storm sewers in conjunction with streets); and (3) direct alteration of stream channels, in order to deal with flooding problems and make land available for development. Creation of impervious surfaces increases the quantity of direct runoff produced by storm events; and all three aspects tend to speed the movement of storm runoff through the surface water system. As a result, the peak rates of stream discharge are increased, often by a factor of 2 or 3 relative to pre-urbanization conditions. One consequence, which is discussed at greater length in Section 9, is a general process of erosion and enlargement of watercourses, ranging from gully erosion at headwater locations to gradual increase in the size of major stream channels. This process involves significant yields of sediment, which add to channel disruption and other problems at downstream points.

The net effects of hydrographic modification are thus: direct disruption of stream channels; indirect disruption due to changes in the streamflow regime; and sediment yields resulting from channel enlargement. These conditions, along with sediment yield from construction sites, are likely to have very important impacts on aquatic life. In the study of Montgomery County, Maryland, streams by Ragan and Dietemann (1975), changes in water chemistry due to urbanization were found insufficient to explain the marked shifts in fish species distribution which had occurred. Primary responsibility was assigned instead to streamflow and sediment as follows (p. 60):

> "Changes in flow regime and sediment load have had a dramatic impact on the stream system. A number of studies reported in the literature have shown that urbanization results in a substantial enlargement of the stream cross-section. A survey showed that Paint Branch, a tributary of the Anacostia, averaged nine feet in 1948, but now has an average width of 37 feet. Much of the gravel-bottomed channel delineated in 1948

> is now covered with silt, and bank erosion has destroyed much of the shelter for fish remaining in the 'unimproved' sections of the streams.
>
> "...A 'river walk' survey conducted as part of the study revealed that approximately 25 percent of the stream length in the Anacostia watershed was either channelized or included substantial construction aimed at bank stabilization. It is believed that the shifts in fish species in the urbanized areas reflect these changes in habitat. Because of the impact that increased rates of runoff have on the streams, on-site detention in storage is a major need in the study area and probably in most other urbanizing watersheds."

Prevention of hydrographic modification, which involves both runoff control and prevention of direct channel alteration, should thus be considered an essential element of stormwater planning, along with control of sediment from construction sites. As implied elsewhere, an important issue is that stream channel phenomena are relevant to loadings of stormwater pollutants generally, due to the role of natural channels as a "sink" for pollutants as well as a source of sediment. In spite of the fact that a large proportion of urban unrecorded pollutant yields are known to involve particulate matter (including chemical pollutants adsorbed onto suspended particles during transport), stormwater planning and research efforts do not appear to be well integrated with ongoing work by hydrologists in sediment transport and river mechanics. Despite the complexity of these subjects, agencies should at least recognize the general importance of channel-related effects, in the design of analytical studies and especially in the formulation of recommended plans for new urban development.

A final comment regarding hydrographic modification is that construction of impervious surfaces tends to reduce streamflow during dry weather, as well as to increase wet-weather flows (although this effect can be offset by imported water, as discussed in Chapter 10). Effects upon base flow may be important to the level of treatment required for recorded effluents, since treatment levels may be sensitive to the amount of dilution received during extreme dry conditions. Hydrographic modification should thus be considered in all aspects of water quality planning; and controls for new urban development should include measures to assure that infiltration and dry-weather flows will be sustained.

Application of Dirt and Dust Accumulation Data

Perhaps the richest available source of information pertaining to urban unrecorded pollution is the literature dealing with dirt and dust accumulation on street surfaces (APWA, 1969; Sartor and Boyd, 1972; Shaheen, 1975). Extensive measurements of contaminant accumulations have been conducted; and methodologies have been developed for utilizing these data to estimate stormwater pollutant loadings (Amy and Pitt, 1974; McElroy, et al, 1975). Several important issues regarding the use of these data are discussed in the following paragraphs.

1. Nonlinearity of Relationships Between Pollutant Accumulation and Time. Methodologies for estimation of stormwater pollutant loadings on the basis of dirt and dust accumulation commonly assume that the amount of material present on impervious surfaces increases at a constant daily rate over time. (Examples are the STORM model, as utilized up until the present writing, and the Midwest Research Institute methodology discussed below.) However, the recent study by Shaheen (1975) of pollutant accumulation on roadways due to vehicular traffic demonstrates that non-linear relationships may prevail, i.e., that the amount of material may approach a limiting value rather than increasing indefinitely between runoff and street sweeping events. Shaheen thus distinguishes between deposition and accumulation of materials on street surfaces, as follows (page 49):

   "Note that, although the deposition of traffic-related materials occurs at a constant rate, the accumulation of materials along the roadway tends to level off after some period of time due, in part, to traffic-related removal mechanisms... However, all of the deposited pollutants are available for transport to receiving waters during storms and the deposition rates are valid estimates of the contributions of motor vehicles to water pollution."

The second statement indicates that, since pollutants removed from street surfaces may still be available for transport by stormwater, it may be appropriate to utilize deposition rates rather than accumulation rates for water planning purposes. This conclusion would not appear valid in all cases, however, since materials transferred to pervious surfaces might reach receiving waters only after long intervals (which would allow time for chemical stabilization), or not at all. The issue of linear versus nonlinear accumulation rates thus remains critical, especially when dirt and dust data are utilized to estimate the pollutant loadings produced by storms which follow long periods of dry weather.

2. Delivery of Washoff Pollutants to Downstream Points. The possibility has been suggested that a major proportion of pollutant loadings in stormwater are deposited in stream channels, rather than transported to downstream receiving waters. This possibility would not necessarily detract from the seriousness of pollutant loadings; in fact, the accumulation of materials in stream channels might result in more critical problems than the conditions created by stormwater pollutants while in transit. However, it is important to note that this factor may cause loading estimates based on dirt and dust data (or on pollutant yields from small catchments) to overstate the seriousness of problems at downstream points, such as problems involving transient dissolved oxygen depletion.

3. Omission of Other Stormwater Pollutant Sources. As discussed elsewhere, washoff of materials from roadways and other impervious surfaces is not the only source of stormwater pollutant yields from urban land, and in at least some cases is not the predominant source. This fact should be kept in mind when utilizing dirt and dust data.

The potential importance of the first two of these issues can be illustrated by comparing, for a number of sample areas, the estimated pollutant accumulations on watershed surfaces with the pollutant loadings observed in-stream. Pollutant accumulations on impervious surfaces have been estimated using a methodology developed by the Midwest Research Institute (McElroy, et al, 1975, pages 186-198), which is based upon information from the URS studies (Sartor and Boyd, 1972; Amy and Pitt, 1974). The urban watersheds considered are the Pennsylvania, New Jersey, and Oklahoma basins discussed earlier (which range in size from 0.1 to 21 square miles, and contain no recorded discharges or combined sewers). Curb length density, required for computation of solids loading rates, has been estimated on the basis of population density for the Pennsylvania and New Jersey basins, using a methodology developed by the American Public Works Association (McElroy, et al, 1975, p. 194).

The first column in Table 5 pertains to the estimated annual deposition of various pollutants on impervious watershed surfaces. Although the Midwest methodology may be intended primarily for analysis of short-term situations, the computation of annual deposition rates should be no less valid than computation of short-term buildup of materials, since the Midwest methodology assumes that buildup occurs at a constant daily rate. (That is, accumulation is not distinguished from deposition in this methodology.) The second column in Table 5 pertains to the pollutant loadings observed in-stream, during all periods in a typical year when surface runoff is present. In each column of the table, only the range of values obtained for individual watersheds is listed.

For the Pennsylvania and New Jersey basins, the estimated rates of pollutant deposition on impervious surfaces tend to be strikingly higher than the in-stream loadings observed during storm periods. In each of four cases--BOD, COD, total phosphate (PO_4T), and ammonia (NH_3)--the range of deposition rates does not overlap with the range of in-stream loading rates, and runs higher than the latter by a factor of about 8. The ratios of deposition rates to in-stream loading rates for individual watersheds range from about 4 to 25. On the other hand, the estimated deposition rates for nitrate (NO_3) are significantly lower than the in-stream loading rates. For the Oklahoma basins, the ranges are much more similar. However, the deposition rates for individual basins still tend to be consistently higher than the in-stream loading rates. The former typically exceed the latter by a factor of 2 or greater for BOD and soluble orthophosphate (PO_4O), and 1.5 or greater for COD.

TABLE 5

COMPARISON OF SURFACE POLLUTANT ACCUMULATION RATES WITH IN-STREAM LOADING RATES

	Loadings in Pounds/Acre/Year	
	Estimated Accumulation on Watershed Surfaces*	Observed In-Stream Loading (Wet Conditions)
Pennsylvania/New Jersey (12 Basins)		
BOD_5	115 - 162	9 - 32
COD	851 - 1139	42 - 159
PO_4T	16.8 - 23.8	0.7 - 4.9
NO_3	4.5 - 6.4	12 - 39
NH_3	15.2 - 21.5	1.1 - 4.4
Tulsa, Oklahoma (15 Basins)		
BOD_5	17.3 - 138	12 - 48
COD	83 - 663	60 - 470
PO_4O	1.3 - 10.6	1.1 - 8.0

* Estimated using methodology developed by Midwest Research Institute (McElroy, et al, 1975)

These discrepancies could be due to the linearity assumption in the Midwest methodology, to settling of materials in stream channels, or to other factors. The figures are cited only to suggest that simplistic application of dirt and dust data to predict in-stream pollutant loadings can potentially result in very large errors, for either short-term or long-term loadings.

Another important point is that the availability of pollutant deposition data should not draw attention away from the need to consider hydrologic conditions when evaluating transient phenomena. In order to illustrate this issue, it is worthwhile to examine in some detail a table contained in the Conclusions section of the Shaheen report (1975, page 5). This table is reproduced here in its entirety as Table 6. For each of a variety of pollutants, Shaheen has estimated the daily mass flow rate per person due to secondary sewage effluent, and the daily rate of deposition on street surfaces due to vehicular traffic, also on a per capita basis. These figures are presented in the third and fourth columns of Table 6, respectively. In the fifth column, Shaheen considers a situation in which three days' accumulation of street surface materials are delivered to surface waters by a two-hour storm runoff event. The relative contributions of sewage effluent and street surface material during this two-hour period are compared by multiplying the latter by 36 (equal to 72 hours divided by 2 hours) and forming a ratio to the sewage flow rate. Traffic is shown to be a much more important source of pollutant loadings during the two-hour period than sewage effluent, for all constituents except BOD, phosphorus, and Kjeldahl nitrogen. Shaheen thus concludes (page 4):

> "Traffic-related deposits by themselves would... constitute a significant source of pollution on a shock-load basis for each parameter listed; thus the importance of traffic contributions to urban water pollution is established."

Although Shaheen's computations are valid, the above conclusion may be misleading, in that the importance of "shock-loading" per se is not established. A two-hour storm period in which all materials on street surfaces are delivered to receiving waters would involve a substantial volume of runoff; thus, stream discharge could be many times

TABLE 6

SIGNIFICANCE OF RUNOFF FROM TRAFFIC-RELATED ROADWAY DEPOSITS TO URBAN WATER POLLUTION

(Comparison with Secondary Sewage Treatment Plant Effluent)

Parameter	Sewage Composition(a)		Average Per Capita Mass Flow Rates		
	Raw (mg/l)	Final Effluent (mg/l)	Final Effluent(b) (g/cap-day)	Traffic-Related Depositions(c) (g/cap-day)	Traffic(d) Impact Ratio (Traffic/Effluent)
Suspended Slids	235	24	9.08	26.3	104
BOD	140	14	5.30	0.06	0.41
COD	200	20	7.57	1.41	6.7
Kjeldahl-N	30	3	1.14	0.004	0.13
Phosphate-P	10	7	2.64	0.016	0.22
Lead	-	0.03	0.011	0.31	1015
Zinc	-	0.08	0.030	0.039	47
Copper	-	0.03	0.011	0.003	9.8
Nickel	-	0.01	0.004	0.005	45
Chromium	-	0.01	0.004	0.002	18

(a) Estimates of raw sewage and final effluent concentrations are for separate domestic sewage and have been derived from Fair and Geyer (4), EPA's manual on phosphorus removal (5) and a recent publication on elemental analysis of wastewater sludges (6).

(b) Average per capita flow rates of pollutants in final effluent have been calculated assuming a per capita flow of 100 gallons of sewage per day.

(c) Average per capita depositions of traffic-related pollutants available in urban stormwater runoff have been calculated assuming a per capita driving distance of 24.3 axle-miles per day and deposition rates of traffic-related pollutants given in Table 1. The per capita driving distance was derived from 1968 figures of 66 x 10^6 axle-miles per day from a population of 2,714,000 in the Washington, D.C. Metropolitan area (7). For example:

$$\frac{5.43 \times 10^{-6}\ \text{lbs. BOD}}{\text{axle-mi.}} \cdot \frac{24.3\ \text{axle-mi.}}{\text{cap.-day}} \cdot \frac{454\ \text{g}}{\text{lb.}} = 0.060\ \text{grams/capita-day}$$

d) Runoff, during a two-hour storm event, of traffic-related materials deposited on roadways over a three-day period has been compared with sewage final effluent discharged to receiving waters during this same two-hour storm.

Source: Shaheen, Donald G. "Contributions of Urban Roadway Usage to Water Pollution." Prepared for the U.S. Environmental Protection Agency. EPA report No. 600/2-75-004. 1975.

higher than during typical dry weather. The greater dilution of effluents could offset the addition of street surface materials, with the result that increases in pollutant concentrations might not occur.

As an example, consider a typical urban watershed in southeastern Pennsylvania with a population density of 10 persons per acre (6,400 persons per square mile). It is assumed that water for domestic supply is imported into the basin from elsewhere; that treated municipal effluent is released to surface waters within the basin; and that sewage effluent and street surface washoff are the only two sources of water pollutants. Under these conditions, streamflow during nonstorm conditions would average about 1.71 cfs per square mile (cfsm), of which 0.99 cfsm would consist of sewage effluent. Based on Sheehan's data, typical pollutant concentrations during dry weather would be as shown in the left-hand column of Table 7. For the two-hour storm period, it is estimated conservatively that a rainfall sufficient to wash off nearly all street surface pollutants would produce at least 0.1 inch of runoff (from the watershed as a whole). Assuming that this runoff is present in the stream system for only two hours--which is also implied by Shaheen--the average discharge during this period would be 34 cfsm. The resulting average pollutant concentrations, produced by both sewage effluent and washoff loads, are shown in the middle column of Table 7. The ratio of each of these figures to the corresponding dry weather concentration is shown in the right-hand column.

The ratios in Table 7 convey a very different impression from that created by the ratios in the right-hand column of Table 6. Given the fact that 2-hour pollutant concentrations must be much higher than long-term concentrations in order to be limiting for aquatic biota, the figures in Table 7 would not necessarily lead to the conclusion that shock-loading would be critical to water quality under the assumed conditions. The purpose of this hypothetical example is by no means to imply that control of street surface contaminants is unimportant. Rather, it is simply to suggest that transient problems due to this source may be less important than simplistic computations would indicate; and that in any case such problems should be analyzed with a high degree of sensitivity to hydrologic conditions.

Measurements of pollutant accumulation on roadway surfaces have clearly performed an invaluable service in raising the

TABLE 7

COMPARISON OF HYPOTHETICAL STORM AND NONSTORM CONDITIONS

	Hypothetical Pollutant Concentrations		
	Typical Dry Weather (mg/l)	2-Hour Storm (mg/l)	Ratio of Concentrations: Storm/Dry Weather
Suspended Solids	13.9	73.5	5.3
BOD	8.1	0.6	.07
COD	11.6	4.5	.39
Kjeldahl-N	1.7	0.1	.06
Phosphate-P	4.0	0.2	.05
Lead	.017	.859	50.
Zinc	.046	.110	2.4
Copper	.017	.009	.53
Nickel	.006	.014	2.3
Chromium	.006	.006	1.0

Source: Betz Environmental Engineers, Inc., based on Table 6 level of knowledge regarding urban runoff problems. There are a number of ways in which such data could be utilized in current water planning studies; and their potential value for this purpose is, of course, a matter of subjective judgment. The opinion here is that use of such data for analytical purposes should generally receive much less emphasis than collection and analysis of in-stream water quality data. As is discussed in Section 7, the latter data would include: (1) chemical and biological information for surface water locations at which unrecorded pollutant sources actually appear to be causing problems; and (2) measurements of pollutant contributions from selected high-yield land areas.

The basis for this opinion is, first, that present predictive methodologies based on deposition and/or accumulation rates do not appear to yield reliable estimates of in-stream pollutant loadings (unless the rates are calibrated using in-stream data), and thus have only limited value for establishing wasteload allotments and determining the pollutant reductions needed to meet water quality criteria. Second, street dirt and dust is only one aspect of the urban runoff problem, albeit perhaps the predominant aspect in a major proportion of areas. This means that the range of control alternatives which can be evaluated using the above-mentioned methodologies is seriously limited. (Admittedly, the effectiveness of many of these potential controls cannot be quantified accurately using any known data sources. The primary concern here is that controls for sources other than streets will be overlooked.) Third, washoff of diffuse materials from streets and other impervious surfaces may be the aspect of urban unrecorded pollution which is least amenable to control. Thus, it may be wise in many cases to focus upon other aspects of the urban runoff problem.

A final comment regarding intensive street sweeping programs, and other broad-scale control measures which entail substantial municipal expenditures, is that implementation of such controls in the short run is likely to depend primarily upon local goodwill and general awareness of water quality issues. Technical inputs such as cost-effectiveness comparisons of control alternatives are not likely to be critical to the implementation of these measures, except perhaps in metropolitan areas with long histories of water planning and currently very well-funded programs. Thus, it can be argued that technical planning efforts be directed primarily toward: (1) gaining a better understanding of existing water quality problems; (2) detecting and documenting the worst source areas, in such a fashion that control can feasibly be achieved even if opposition occurs; and (3) developing highly selective control measures which do not entail major public or private cost. These issues are discussed further in Section 7.

Localized Pollutant Sources

Discussion of pollutant loadings due to urban land drainage has tended to emphasize pollutant-generating factors which are relatively ubiquitous in urban areas. A typical example is the following description by Loehr (1974):

> "Street litter, gas combustion products, ice control chemicals, rubber and metals lost from vehicles, decaying vegetation, domestic pet wastes, fallout from residential and industrial combustion products, and chemicals applied to lawns and parks may be sources of contaminants in urban runoff."

A concern here is that such discussion may have created the impression in some minds that the relevant control measures for urban runoff problems are limited to actions which affect pollutant generation from extensive land areas. Although such measures may in fact be necessary, it is important to note the potential role of localized, or "site-specific," pollutant sources which can be addressed by fundamentally different types of controls. Site-specific sources can be defined loosley as pollutant sources which: (1) yield relatively large quantities of pollutants relative to the land area involved; and (2) are not necessarily associated with general types of land use or economic activity.

The importance of continuous sources (i.e., non-SRA sources) fitting this description is commonly recognized; two examples are malfunctioning on-site septic systems, and landfills which produce significant quantities of leachate. The existence of site-specific SRA sources appears to have received relatively little attention, however, due in part to the fact that very few studies of urban runoff pollution have attempted to determine the specific origin of pollutant loadings in a given watershed. One case in which a detailed investigative process was carried out is considered highly instructive, and thus is described here in detail. In 1969, the Water Resources Research Institute at Rutgers University began an intensive study of BOD loadings from unrecorded pollutant sources in urban areas of New Jersey. Several small, predominantly residential basins with no known effluent discharges were selected for study, one of which was the Mile Run watershed in New Brunswick. The findings were reported as follows (Whipple, et al, 1974, pp. 26-31).

> "The upstream portion of Mile Run above its Livingston Avenue crossing was chosen for study since it drained an area which was predominantly residential in character and seemed to contain no gross pollution...This drainage area selected is approximately one mile square, of which 38.5% is devoted to residences, and only 19.2% to industrial and commercial uses. Street surface area accounts for some 14.0% of total land...
>
> "During the early sampling of Mile Run, certain peculiarities were noticed. Heavy oil slicks were observed to occur during rainstorms with strong odors of fuel oil at the gaging station. In addition, BODs were running approximately three times what was expected. A COD test run on a sample on November 7, 1969, showed a relatively high result. This was the first indication of organic loading other than street runoff. On November 10, 1969, samples were taken at Georges Road and Livingston Avenue on a non-rain day. The results were revealing (see Table III-1). The BOD at Georges Road was some six times the BOD at Livingston Avenue. In addition, the pH at Georges Road was abnormally high. On November 14, 1969, for a relatively small rainfall a BOD above 25 mg/l was recorded, again considerably high. It was concluded that there was some additional source of pollution affecting data collected on Mile Run.
>
> "The source of the organic load imparted to the stream was investigated to locate the area and the possible source...On March 10, 1970, the BOD concentration was above 100 mg/l at Georges Road and the temperature difference was 11 degrees C from the Livingston Avenue sample...Obviously, some heated organic load was entering above Georges Road crossing...
>
> "An on-site investigation was conducted to determine the possible source along the stream banks on the morning of April 28, 1970. The investigation revealed

> a small hot water source, possibly accounting for the temperature rise at Georges Road, and fuel oil pollution, obviously entering in the Ward Street-Fulton Street area due to fuel oil commerce in the area. Drainage ditches in that area were heavily coated with sludge fuel oil which emptied into Mile Run during times of runoff and appeared to be dumped into ditches as waste. The north bank of Mile Run in this area appeared to be leaking oil from its bank and there was evidence of waste oil being dumped from atop the bank. What was difficult to determine was the cause of a heavy brown scum buildup at two locations in the stream just below Squibb and just below Georges Road.
>
> "Obviously the pollution in Mile Run is far greater than can be attributed to the housing. The mean 5-day BOD during a two-year period of observation was about 9 mg/l in dry weather and 17 in wet weather. The average BOD loading varied to a much greater extent, being about 26 lbs/day/sq. mi. in dry weather and about 800 lbs/day/sq. mi. in wet weather, giving a weighted mean annual BOD loading of about 277 lbs/day/sq. mi. It is apparent that the storm runoff is of controlling importance. The changes in suspended solids and COD during rainfall are even more dramatic than those of BOD...The influence of industrial wastes was evidenced not only by the high BOD, but also by direct observations of heated and colored discharges, banks darkened with oil, oil slicks and rapid changes in BOD at certain times of the day.
>
> "It is apparent that the pollution levels in such areas are mainly dependent upon the degree and kind of commercial and industrial development, and the effluent controls employed. No methodology can be visualized to forecast such loadings from commonly available planning parameters."

The Mile Run case is clearly an extreme rather than a typical situation. The important point, however, is that site-specific sources such as these could be operative on a smaller scale in many areas. Two critical characteristics of these sources are the following. First, as indicated by the last sentence of the above quote, their effects are difficult to predict and identify on the basis of generalized relationships or modeling programs. (Note that, unless unusually detailed calibration procedures and monitoring were utilized, a stormwater model would attribute the pollutant loadings in Mile Run to ordinary washoff or erosion processes, or else would leave the high loadings unexplained.) Second, the controls which are appropriate for these sources ordinarily consist of very selective measures. Broad-scale controls tend to be either irrelevant, as would be true for street sweeping in the Mile Run case, or unnecessarily inefficient, as would be true in this case for runoff detention and treatment. Several classes of site-specific sources with these characteristics can be identified as follows.

Dumping of liquid and solid waste on land surfaces. Waste disposal or storage of pollutant-generating materials on land surfaces can occur either on-site or off-site relative to points of waste generation (e.g., homes or businesses). Whether or not such activities involve impervious surfaces, an important distinction from other pollutant sources is that localized waste accumulations tend to be less costly to remove than diffuse materials such as street dirt; and there is generally a higher probability that further accumulations can be prevented.

Major sanitary sewer leaks and bypasses. Pollutant generation by sanitary sewer systems, other than combined sewer overflow and discharge of treated effluent, is important in many areas. Potential problems include both sewer leakage during dry weather, and major overflows during wet conditions due to inflow of stormwater. Lager and Smith (1974, p. 67) have described separate sewer systems in the following way:

> "Most sanitary sewers in the United States are de facto combined sewers. Stormwater enters these sewers through cracks, unauthorized (and sometimes authorized) roof and area drains, submerged manhole covers, improperly formed or deteriorated joints, eroded mortar in brick sewers, basement and foundation drains, and poorly constructed house connections."

Inflow of surface and groundwater during wet conditions may cause total wastewater flow to exceed the capacity of pipes, pump stations or treatment plants downstream, with the result that bypasses are necessary. In many communities, bypasses have been created on a casual basis, without records being kept as to location and design characteristics.* The extent of these problems, which are important primarily for older urban areas, may be difficult to predict on the basis of generalized relationships, although empirical information for this purpose has been developed by some private consulting firms.

Direct discharge of liquid waste to storm sewers and receiving waters. Many of the pollutant-generating activities included in this category are illegal according to federal, state, or municipal statutes, but nevertheless occur. Unauthorized discharges to surface waters may be either intermittent or continuous, and may or may not involve fixed conveyance facilities. An example of intermittent discharge without conveyance facilities is dumping of septic system waste into surface waters by professional scavenging operations. An important problem in some areas is illegal connections to storm sewers, which allow untreated wastes to pass more or less directly to receiving waters. Improper use of storm sewers and underdrains for disposal of wastes such as crankcase oil is also not uncommon.

Discharges in excess of permits. Even effluent dischargers presently covered by permits can constitute unrecorded pollutant sources if the discharge levels exceed permitted amounts. This can occur for a variety of reasons, including accidental spills and treatment system malfunctions. Although it is not possible to generalize regarding violation of NPDES permits, a relevant observation is that the estimates of "nonpoint source" pollutant loadings which are inferred in mass-balance and modeling studies are often significantly higher than loadings observed in comparable basins without recorded effluent dischargers.

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* In Allegheny County, Pennsylvania, for example, over 600 known sewer bypasses have been identified, and the actual number of bypasses is estimated to be much greater. (Personal communication with Dennis Burke, P.E., of The Chester Engineers, Coraopolis, Pennsylvania.)

The importance of these localized sources relative to other unrecorded pollutant sources is difficult to judge except on a case-by-case basis. However, the present study has yielded one item of evidence which suggests indirectly that sources other than washoff of diffuse materials may be generally significant. Chemical data for the 15 urbanized basins in Tulsa, Oklahoma, cited earlier have been subjected to a pooled regression analysis in which individual pollutant concentrations were related to precipitation variables such as: time since start of rainfall, average intensity of rainfall, and time since the previous storm. The most notable finding was a failure to observe strong positive associations with time since the previous storm, even when the other factors (which did bear strong relationships to pollutant concentrations) were controlled. Association with time since the previous rainfall would be expected if water quality is dominated by sources for which the available supply of pollutants fluctuates markedly with the occurrence of storm events--as tends to be true for street dirt and similar materials. This finding, which has been noted in a few other studies, could be due partly to nonlinearity of pollutant accumulation rates, but is nevertheless considered significant. (Further discussion is contained in the Technical Appendix.) The conclusion is that the nature of stormwater pollutant sources should be considered carefully in each case, rather than simply assumed.

Conclusions

The present summary review has dealt primarily with pollutant generation; an extensive discussion of water quality issues is contained in the Technical Appendix. The overall conclusion is that loadings and problems due to unrecorded sources are highly variable, and may be due to site-specific factors as well as to factors such as traffic and litter which are generally ubiquitous in urban areas.

Agencies with limited resources may be well-advised to avoid focusing upon transient water quality problems which occur during and immediately after surface runoff events, unless such problems are directly demonstrated to be important. Dissolved oxygen has historically been over-emphasized in water planning; a carryover of this pattern to analysis of unrecorded pollution problems could be unfortunate since transient DO phenomena are especially difficult to predict and evaluate. With regard to other "shockload" effects of urban runoff, the importance of these effects may not be demonstrable even if temporarily high pollutant concentrations are established, due to the extreme lack of knowledge regarding response of aquatic biota to conditions lasting less than 24 hours. (Note that high concentrations due to "first flush" effects are usually very short in duration, when receiving waters consist of free-flowing streams.) An important point is that transient impacts are highly sensitive to receiving-water characteristics, and therefore should not be a major focus of analysis unless an agency is prepared to consider these characteristics in detail.

Given the fragmentary data reviewed here, it appears reasonable to hypothesize that analysis of transient problems per se is usually not essential in urban areas which do not contain combined sewers or notably poor environmental conditions, and for which the receiving waters do not consist of estuaries or standing water bodies.* The alternative is to focus upon the long-term problems created by SRA and non-SRA sources, utilizing annual and/or seasonal pollutant loading estimates. Preparation of such estimates on the basis of observed data does not necessarily require the use of loading simulation models. Similarly, analysis of the effectiveness of control measures for both SRA and non-SRA sources can be conducted on a long-term basis, using tools such as the Hydroscience methodology cited in Section 9.

It is true that existing water quality criteria in some areas are limited largely to dissolved oxygen and pathogens. However, current water quality management planning studies are not compelled to perpetuate the biases of the past. An extremely important output of these studies could in fact be the recommendation of additional criteria which will provide more adequate protection of water quality.

An important finding of the present review is that the water quality impacts of new urban development, once in place, may be substantially less than the average effects of existing development. Given this finding, it is considered feasible to adopt a strategy for new development in which many of the major control measures would be based explicitly upon water quantity considerations rather than water quality *per se*. This strategy is outlined in detail in Section 9. With regard to existing water quality problems, the recommended strategy when technical planning resources are limited is to devote these resources primarily to analysis of: (1) instream water quality problems; and (2) selected high-yield pollutant sources. This approach and its underlying rationale are discussed in Section 7.

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* A major exception to this generalization may be urban areas located in climatic regions where rainfall is not well-distributed throughout the year. Extended pollutant buildup on impervious surfaces may cause transient DO problems to occur widely in these areas even if there is reasonable public cleanliness.

SECTION 6

REVIEW OF PLANNING METHODOLOGIES

Introduction

The ultimate goal of the present project has been to develop a "planning methodology" for use in water quality management planning studies. Such a methodology is defined broadly as any systematized approach which provides assistance in quantifying present and future water quality problems, and in evaluating possible control strategies. As noted earlier, the present emphasis is upon urban land, particularly the impacts of future urban development. A broad objective of the planning methodology is to promote and facilitate the use of preventive water quality control measures.

This section discusses the planning methodologies which have been reviewed. The four general types of methodologies considered are the following: (1) environmental synthesis techniques (e.g., suitability mapping); (2) stormwater modeling; (3) development and use of statistical relationships; and (4) other predictive tools. As a result of this review, and the review of urban stormwater problems discussed in Section 5 and in the Technical Appendix, the present report will recommend the use of a variety of predictive tools, rather than a single unified methodology. Suitability mapping and similar techniques are found not to be favorable for general use in water quality management planning studies, because they do not directly address the technical issues which are felt to be most important. The value of statistical studies is limited by the data requirements involved and the fact that the relationships obtained may not be useful for evaluation of controls. One reason for not focusing on stormwater modeling in the present report is simply that the subject has been treated extensively elsewhere (e.g., Meta Systems, 1975). Modeling is also found to have a number of liabilities, particularly when planning resources are limited. The discussion in the latter portion of this document will therefore stress the use of other methodologies.

Stormwater Modeling

As introduction to some of the basic issues involved in stormwater analysis, it is worthwhile to consider briefly the distinctions between deterministic modeling--of which stormwater modeling is representative--and stochastic modeling. The essence of deterministic modeling is an attempt to provide direct mathematical representation of causal linkages. Model equations are formulated on the basis of *a priori* knowledge and intuitive judgment; an important criterion is the existence of direct parallelism with physical phenomena. In contrast, stochastic modeling involves development of equations on the basis of empirical data, utilizing statistical techniques. A stormwater model which attempts to predict pollutant loadings from a particular type of source area, for example, might provide separate equations describing the washoff process and the transport of pollutants through each link of the drainage system; whereas a stochastic model might involve only one equation, estimated statistically on the basis of repeated observations of source area characteristics and pollutant loadings. The distinction between deterministic models and stochastic models (notwithstanding the use of statistical techniques in the latter case) is not always pronounced, since calibration to observed data is a common characteristic of deterministic modeling, whereas a strong theoretical basis is sometimes available for development of stochastic models. Nevertheless, the difference in emphasis is very important.

The appropriateness of deterministic versus stochastic modeling depends upon the complexity of the phenomena under study and the level of knowledge which exists. Stochastic modeling is clearly appropriate in economics, for example, since it would be impossible to trace all of the individual dollar flows and corresponding activities which comprise an economy. Thus, in an econometric model, a quantity such as personal consumption expenditures would be related to disposable income and other aggregate variables (many of which could be highly artificial constructs) which are demonstrated statistically to bear some association with personal consumption. The potential weaknesses of stochastic modeling are that: (1) large amounts of data are necessary for model development; (2) the meaning of the relationships obtained may be obscure; and (3) the predictive accuracy of stochastic models may be poor--particularly in cases where certain real-world quantities are to be manipulated for the purpose of system control. On the other hand, the potential weakness of deterministic modeling in dealing with complex situations is that a lack of empirical investigation prior to model development may lead to oversimplification and over-structuring of the phenomena under study, with the result again that predictive accuracy and value for analysis of controls may be limited. The latter limitation, when it exists, tends to be more subtle than in the case of stochastic modeling, and often goes unrecognized, due to the fact that the relationships in deterministic models are typically designed so that input of control actions *per se* does not present difficulties.

With regard to the study and control of urban unrecorded pollution problems, it is felt that the usefulness of both deterministic modeling and stochastic modeling is seriously restricted, due to the issues just discussed. The basic problem in the case of deterministic modeling is a lack of *a priori* knowledge--referring primarily to documentation of conditions relevant in specific instances, rather than knowledge at a theoretical level. The problems in the case of stochastic modeling (discussed in a later sub-section) are the difficulty of obtaining an adequate base of empirical data, and the inherent limitations of this approach for evaluation of control measures. On the whole, it may be premature to rely heavily upon formalized analytical procedures in dealing with unrecorded pollution problems other than known sewer system overflows.

The present review of stormwater modeling will focus upon only two computerized models: SWMM and STORM. The discussion is also relevant, however, to the use of simplified techniques which incorporate similar assumptions. The Storm Water Management Model (SWMM) has been developed under the auspices of EPA and is expected to play a major role in water quality management planning studies. STORM was developed as a planning tool by the U.S. Army Corps of Engineers. SWMM is highly comprehensive in that it includes sophisticated routines for flow routing and simulation of receiving water response (e.g., dissolved oxygen depletion). In contrast, STORM is relatively simplistic and is concerned primarily with pollutant generation. An important feature of STORM is that it permits long-term simulation of runoff quantity and pollutant loadings, whereas SWMM must be applied to pre-selected design storms. Both models are designed to permit evaluation of control alternatives, such as street sweeping, runoff storage and treatment, and other structural controls (in the case of SWMM).

An aspect of stormwater models which is particularly important for the present discussion is the manner in which the models treat acquisition of pollutants from land surfaces (as opposed to sewer system overflow, the other major category of unrecorded pollutant generation considered by SWMM). SWMM and STORM consider two basic mechanisms: washoff of accumulated dirt and dust from impervious surfaces, and erosion of material from pervious land. Washoff of material from impervious surfaces tends to receive primary attention when the models are applied to urban watersheds. The design storms utilized for planning purposes may in fact be defined specifically as rainfall events which produce direct runoff from impervious surfaces but not from pervious land.

In both SWMM and STORM, pollutant yields due to washoff are represented as the sum of three components: dissolved material, suspended material, and settleable material. The models assume that the rate of removal of dissolved material from a surface at any given time during a storm is positively related to the amount of material present on the surface at that time, and the rate of stormwater runoff at that time. For suspended and settleable material, the rate of removal is also positively related to the availability of material for transport, which is considered to be a positive function of the runoff rate. A characteristic of this formulation is that, when only the suspended fraction is considered, the implied pollutant concentrations are negatively associated with time since start of storm, and negatively related to the rates of precipitation and runoff (except at the very beginning of rainfall). The model thus describes a "first flush" effect. When suspended and settleable materials are considered, however, it is mathematically possible to reproduce almost any pollutograph shape.

The most critical determinant of pollutant loadings and concentrations due to washoff is the amount of material present on impervious surfaces at the start of a storm. The STORM model simulates changes in the amount of this material over time. Dirt and dust are assumed to build up continually on impervious surfaces, and be removed at discrete intervals by storm events and by street sweeping. In the case of SWMM, it is necessary to supply dirt and dust information for each individual storm event considered (unless SWMM is linked to STORM in the manner suggested by Meta Systems). An obviously important issue in applying STORM is the possible nonlinearity of dirt and dust accumulation over time. As noted in the previous section, Sheehan (1975) has shown that pollutant buildup on roadway surfaces is likely to bear a nonlinear relationship with time, approaching an upper limit rather than increasing indefinitely. On the other hand, he suggests that the deposition rate (a constant daily rate) may nevertheless be more relevant than the accumulation rate, since pollutants removed from roadways may still be available for transport by stormwater. In any case, STORM incorporates a constant daily dirt and dust accumulation rate, as of early 1976. The emphasis of STORM and SWMM on washoff of diffuse materials from impervious surfaces makes these models potentially very sensitive to the timing of storms. The pollutant loadings and concentrations predicted for isolated storm events can be an order of magnitude higher than the values for storms which occur in rapid succession.

Erosion of soil and associated pollutants from pervious land, when this factor is considered, is modeled in both SWMM and STORM by the Universal Soil Loss Equation (USLE), which is discussed elsewhere in this report. The only transient factor in the USLE relating to hydrologic conditions is the rainfall intensity factor, which expresses the ability of rainfall to detach and transport materials from the soil surface. A significant fact is that, since pollutant accumulation processes are not involved in this case, the pollutant loadings predicted by the USLE are not sensitive to the timing of storms.

A point which is obviously relevant to the use of SWMM and STORM is the fact, discussed in the previous section, that washoff of diffuse materials from impervous surfaces, generalized land erosion, and combined sewers are not the only unrecorded pollutant sources affecting urban water quality during storm periods. Sanitary sewer bypasses, outflow of contaminated groundwater, accidential spillage, overflow of on-site septic systems, unauthorized and excessive wastewater discharges, and other factors can be important. Even when washoff and erosion from land surfaces are dominant, the relative importance of individual source areas and source types may be a critical issue. An industrial docking area (impervious) or an unregulated dumping area (pervious) may yield pollutant loadings that are an order of magnitude higher per unit area than the loadings from ordinary streets, lawns, and parking lots. Theoretically, all of these factors can be represented in stormwater models (although STORM is much more limited than SWMM in this regard). Model structure per se is not necessarily constraining. The important issue is that source identification is rarely an integral feature of modeling studies, except perhaps for analysis of sewer system characteristics. Model calibration and source identification are by no means the same thing, since calibration data usually reflect a variety of pollutant sources. As a result, the typical situation in modeling studies is that all pollutant loadings which are not accounted for by combined sewers, recorded discharges, and known sanitary sewer bypasses are attributed to generalized washoff processes (and possibly general land erosion if the USLE is utilized). This situation may or may not affect the ability of the models to predict in-stream pollutant loadings and problems. However, the failure to isolate specific sources and source types has serious implications for the evaluation of control measures.

The cases in which conventional modeling studies are likely to be most successful are thus: (1) areas where sewer system outflow accounts for a large proportion of pollutant loadings, and is well-documented; and (2) urban core areas where washoff of diffuse materials from street surfaces can be safely assumed to account for most pollutant loadings (due to the high level of street activity, and the general absence of pervious land and exposed watercourses). These issues are considered further below, after discussion of model calibration.

Other aspects of stormwater models besides pollutant generation are, of course, important. The major elements of SWMM consist of a highly sophisticated hydraulic transport, storage, and treatment model, and routines for simulation of dissolved oxygen dynamics. There are a number of critical issues regarding simulation of receiving water response which could be discussed, such as the ability of the model to predict transport and deposition of particulate materials in natural channels, and the appropriate values of parameters such as deoxygenation and reaeration rates. The present discussion will be limited, however, to the "front end" aspects of the models, i.e., the manner in which they deal with pollutant generation.

Need for Model Calibration and Verification

Calibration of stormwater models--i.e., the use of empirical water quantity and quality data to infer appropriate values of the model parameters--tends to constitute a very large proportion of total modeling costs. Given that default values are supplied for most parameters, calibration is not strictly necessary to obtain outputs. Thus, it is worthwhile to consider the need for calibration in some detail. Since the objective of calibration and verification is to increase the accuracy of a model in describing real-world situations, a major issue is the extent to which accuracy is actually required for planning purposes.

The potential functions of stormwater modeling as a technical planning tool could be categorized as follows: (1) analysis of the magnitude and timing of pollutant inputs from various sources; (2) prediction of pollutant loadings and concentrations at in-stream points where problems occur; (3) simulation of water quality problems (e.g., oxygen depletion) which result from complex interactions of pollutant loadings and other factors; and (4) analysis of system response to control measures, and comparison of different controls in terms of effectiveness. The first three of these functions involve description of water quality under existing conditions. The use of modeling for such descriptive purposes is limited primarily to cases in which model outputs are cheaper or otherwise more feasible to obtain than direct water quality data (for example, cases in which great spatial detail or coverage is required, or when the necessary information pertains to infrequent events). Predictive accuracy is clearly important when these descriptive functions are emphasized.

The fourth function listed above, the use of modeling to evaluate potential control measures, commonly receives primary attention in the design of modeling programs. The need for predictive accuracy in this case is somewhat debatable. It is argued that stormwater modeling can be useful for comparative evaluation of controls, even if the model is not successful as an absolute predictor. Three comments can be made regarding this position. First, models which do not replicate real-world conditions reasonably well cannot establish the overall levels of control needed. That is, comparative evaluation of control measures will not necessarily indicate the ability of a set of controls to achieve absolute water quality standards. Second, tests of predictive accuracy are often the best means of demonstrating that underlying causal relationships are specified correctly in the model, including relationships that affect the relative performance of control measures. Third, the extent to which predictive accuracy can be claimed for analytical methodologies utilized in planning could have an important bearing on the implementation of controls, in cases where recommended plans are controversial. The arguments which discount the need for predictive accuracy in modeling may be based on an implicit assumption that implementation of recommended plans is not an issue--that the major question is simply the choice from among available control alternatives. Such a description may not apply to current water quality planning programs (as is discussed in the next section). Given these factors, it is felt here that predictive accuracy should be an explicit objective of stormwater modeling, if modeling is to be undertaken at all. However, this is admittedly a matter of opinion.

SWMM and STORM clearly require calibration in order to simulate water quality phenomena accurately, although SWMM may be a good hydraulic predictor with little calibration. Possible sources of error in the pollutant loading estimates yielded by these models are the following: (1) failure of dirt and dust accumulation data from the literature to describe local conditions; (2) inaccurate specification of dirt and dust buildup processes; (3) omission of unrecorded pollutant sources other than street dirt (and general soil erosion, if the USLE option is utilized); and (4) failure to consider the potential significance of pollutant losses during transport. Both STORM and SWMM incorporate default values of dirt and dust accumulation rates based on the original Chicago study (APWA, 1969), which could be replaced by more recent, regional data. This might not reduce the need for model calibration, however. A consequence of the discussion in Section 5 is that direct measurements of surface dirt and dust may not relate well to in-stream water quality.

In general, the usefulness of uncalibrated models is felt to be limited to the following tasks: (1) demonstrating to a receptive audience that certain problems do exist; (2) selecting control measures when there is widespread agreement regarding both the seriousness of the problems addressed and the sources responsible; and (3) dealing with water quantity problems. An example of the second case is use of the USLE to develop controls for erosion from construction sites (see Section 11 of this report). Here, neither the pollutant source nor the resulting problems are likely to be a major subject of controversy; the principal planning task is to design and implement appropriate controls. It is relevant that erosion/sedimentation controls can be successfully implemented without any quantitative analysis of water quality impact, as has been demonstrated in a number of communities.

A final point which should be noted in this context is that, if accurate stormwater modeling is judged to be infeasible in any particular case, the alternative is ordinarily not to substitute another methodology that yields similar outputs (which may not exist). Rather, the alternative is to rephrase the questions that are being asked, so that fundamentally different analytical techniques can be employed. This point is discussed further below.

Model Calibration Procedures

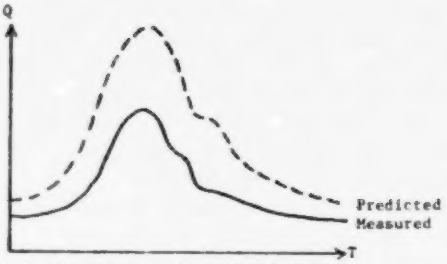
Model calibration consists of a process wherein the model parameters, and occasionally the input data describing the hydrologic system, are adjusted so that water quantity and quality predictions are consistent with observed data. Verification consists of comparing predictions with reality for cases which have not been considered in the calibration process. In regional water quality planning studies, model calibration programs can be oriented toward two somewhat different objectives: (1) developing an accurate model for a given basin or water body; and (2) developing general values of model parameters, which can be widely applied in modeling applications throughout the region. The model parameters which are principally referred to here are dirt and dust accumulation rates. In either case, the typical situation is that adequate water quality and quantity data for model calibration do not exist prior to a model study. Thus, the first step is commonly to design and execute an intensive stormwater monitoring program.

A systematic procedure for SWMM calibration and verification has been developed by Dr. James Hagarman of the University City Science Center, Philadelphia. This procedure illustrates the steps necessary to obtain generalized model parameters, and is generally indicative of the important issues involved in stormwater modeling.

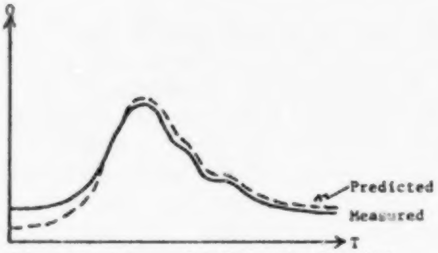
The areas used for model calibration in this procedure are small catchments (less than 100 acres) which contain uniform or nearly-uniform land uses. The overall set of areas chosen is intended to be representative of land uses found within the study area. Data are collected for about a half a dozen runoff events, for the duration of each event. The data include both quantity and quality of runoff, as well as the rainfall hyetograph. For each area, detailed measurements are made of imperviousness, curb length, slopes, and other characteristics relevant to hydrologic response. If an area is serviced by a combined sewer system, dry weather flow data are collected for calibration of sanitary flows.

The calibration procedure starts with water quantity; after quantity, quality is calibrated. Although there are no set rules as to which program parameters to adjust during flow calibration, there are some guidelines. Sensitivity analysis has shown that the percent of land impervious has a very significant effect on quantity. This factor is sometimes treated as an adjustable parameter, even though it is physically measurable, since the adjustments can be considered to express interactions between pervious and impervious areas. Infiltration rates can also be adjusted. Such parameters as pervious area resistance factors and surface storage depth have almost no effect on the outfall hydrograph. Figure 5 gives some examples of program response to input parameters. Generally, measurable data besides imperviousness should not be varied. For quality calibration, the dust and dirt accumulation rates, and the pollutant composition of dust and dirt, are the major adjustable parameters. (If default values of these parameters are to be utilized, it is extremely important to assure that the conditions on which the values are based resemble conditions encountered in the study area.)

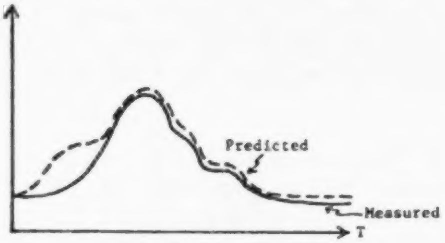
Following the calibration of the model is a two stage verification process. The first stage is the application of the model to a small, multiple land use basin using detailed information. If the results of this stage are not satisfactory, it is necessary to examine carefully the assumptions made during the model calibration stage. If the results are satisfactory, the second stage of verification can be implemented. This involves application of the model to a larger basin with multiple land uses, using less detail than before in representing basin characteristics. The description of this basin may be facilitated by correlations developed during the calibration stage (such as percent



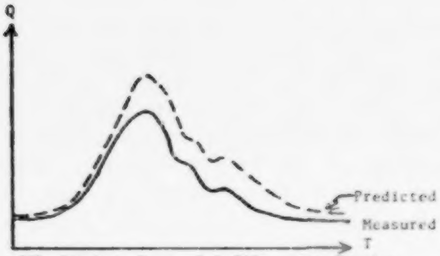
(a) Percent Impervious Area Too High



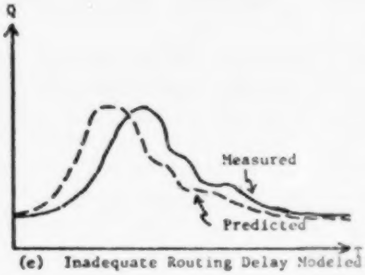
(b) Initial Rate of Infiltration Too High



(c) Decay Rate of Infiltration Too High



(d) Minimum Rate of Infiltration Too Low



(e) Inadequate Routing Delay Modeled

Source: Jewell, T.K. and P.A. Mangarella, "Applications of Stormwater Management Models," EPA Short Course Study Guide, University of Massachusetts, p. 45, 1975.

Figure 5 RESPONSE OF SWMM PROGRAM TO INPUT PARAMETERS

imperviousness as a function of land use). Again, if the results of this test are unsatisfactory, the initial assumptions must be closely examined.

After calibration and verification, the model can be applied to the entire study area, using the less detailed methods developed in the second stage of verification. For a selected design storm or storms, the model can generate inputs to river models and aid in developing abatement plans. The calibration and verification process tends to be costly. As an example, this methodology is being utilized in a major Eastern metropolitan area at a cost of about $70,000 for 12 basins. Of this total, about 50% is for data collection, and the other half is for data reduction and computer charges (i.e., actual modeling costs). This figure does not include the cost of monitoring water quality and quantity for the test basins--which is expected to exceed the sum of land measurement and modeling costs. Thus, the total cost of model calibration is in the vicinity of $150,000.

This procedure represents a state-of-the-art approach for obtaining model parameters that are specific to land uses. In other modeling applications, calibration is conducted at a grosser level, with the result that pollutant loads cannot be assigned to specific land uses and source areas. However, as suggested earlier, even a very detailed calibration program such as just described does not necessarily constitute a process of source identification. It does not establish the relative pollutant contributions of streets, other impervious surfaces, and unrecorded pollutant sources besides washoff. This issue is especially important when dealing with industrial areas, and medium-density urban development in which the overall imperviousness of land is less than 50%.

Consider, for example, the situation when a model is calibrated for a basin in which water quality during storms is affected importantly by a source such as an unregulated dumping area or an unidentified sanitary sewer overflow. The pollutant loadings from this source are likely to be attributed to dirt and dust accumulation. If the calibration process is especially sensitive, the loadings might be attributed to erosion by way of the USLE option, to account for certain aspects of their behavior (e.g., the fact that loadings are negatively rather than positively correlated with time since previous rainfall). In either case, the nature of the source, and the potential effectiveness of selective control measures, would not be identified by the calibration process per se. To consider a less extreme example, suppose that accumulation of materials on impervious surfaces is in fact the predominant pollutant-generation mechanism in a basin, but that a few areas are responsible for a disproportionate share of the loadings. The dirt and dust accumulation rates obtained through model calibration would be general rates, applying to the basin as a whole, and might not be accurate in describing land conditions at any particular point. The two aspects of modeling which are illustrated by these examples are the following:

1. Stormwater modeling does not necessarily deal with pollutant generation at the level of detail which is relevant for evaluation of selective land management controls.

2. The dirt and dust accumulation rates which are obtained through model calibration must be viewed largely as artificial constructs, whose correspondence with land surface conditions is unknown.

The relevant level of detail for evaluation of controls is the specific land surface or activity to which a control will apply. Evaluation of streetsweeping programs, for example, requires that pollutant loadings from street surfaces be isolated from all other influences on stormwater. Conventional modeling activities will not accomplish this; but neither will any other methodology which is not based upon extremely source-specific data. The point is that the structural capability of a model to evaluate streetsweeping programs might not justify its use if a required step in performing such evaluations is to make a bald assumption as to whether street surfaces account for, say, 40% or 80% of the total pollutant load in any given case. The issue here is not the relative merits of modeling versus other methods of data manipulation, but simply the fact that model calibration is not necessarily the same as source identification.

Results of Model Testing

Model verification studies have indicated that SWMM and STORM may be reasonably accurate in predicting runoff quantity. Relatively little can be said about their ability to predict runoff quality, however. Remarkably little testing has actually been conducted using observed water quality data. The SWMM manual reports testing of water quality predictions in four areas, with good results obtained in two cases. On the whole, the accuracy of SWMM in predicting water quality can be described as "questionable" (McElroy et al, 1975, p. 5-29). The same would apply to STORM. A reasonable hypothesis with regard to the ability of SWMM to predict pollutant generation is that performance is relatively good for combined sewer overflows, due to the fact that discharge quantities are the most critical issue in this case, but that predictive accuracy is more questionable for other unrecorded pollutant sources.

An aspect of stormwater modeling which is relevant to current planning efforts is that water quality modeling in general is a specialized skill. Considerable experience is required in order to be able to calibrate and operate models effectively. This is true for steady-state oxygen modeling, and therefore should hold to an even greater extent for attempts to simulate dynamic receiving-water conditions during and after storm events.

Overall Evaluation of Modeling

The decision as to whether stormwater modeling should be utilized in a given situation is ordinarily not a straightforward choice between modeling and some other comparable planning technique. No technique may exist which can substitute directly for modeling, in the sense that no other technique may be capable of generating the same types of outputs or of evaluating the same variety of control options within a single framework. The alternatives to stormwater modeling therefore tend to involve fundamentally different planning approaches, in which different aspects of urban water quality problems are emphasized. The choice which confronts planners in this regard is explored in Section 7. The following are some general comments.

1. The fact that modeling theoretically allows crisp evaluation of control alternatives may have limited significance if the underlying pollutant-generation mechanisms are not well understood, as is typically the case for urban stormwater. Unless a detailed process of source identification is carried out along with model calibration, the reliability of models in evaluating spatially-selective land managment controls may be highly suspect.

2. The fact that modeling allows comprehensive evaluation of different forms of pollution control may be less important than is commonly supposed, in part because land management controls constitute a weak link in the evaluation process, and in part because of the nature of current planning programs. The ability to analyze many different options within a single framework has greatest value in cases where planning objectives, constraints, and criteria are clearly defined--as when a "best" plan is to be selected and implemented by a single actor. In present water quality management planning, however, a large number of actors are typically involved; and issues involving implementation feasibility are likely to assume overriding importance.

3. Stormwater modeling is not necessary for evaluation of long-term problems due to unrecorded pollutant sources, as opposed to transient problems which occur during and immediately after storm events. Although some models can be utilized to generate annual and seasonal loadings, they tend to be relatively inefficient for this purpose.

The modeling question, as confronted in regional water quality planning studies, largely boils down to the allocation of planning resources among various types of activities. Modeling is not inexpensive. The resources devoted to model calibration and operation could be used instead for collection of additional field data, design of pollution control alternatives, investigation of pollutant sources on an individual basis, management and institutional analysis, or many other possible tasks. Given this fact, and the issues mentioned above, it is felt that stormwater modeling should probably be limited to cases in which end-of-the-pipe control measures for unrecorded pollutant sources are considered a realistic possibility in the near future. A hypothesis offered here is that such cases are limited for the most part to areas containing combined sewers and/or very high-intensity urban development (see the next section).

The use of STORM is considered especially dubious, since this formulation emphasizes the aspects of urban unrecorded pollution which are least amenable to modeling, given present knowledge. The model itself (as of early 1976) contains a number of unrealistic features, such as Hortonian hydrology, linear dirt and dust accumulation rates, and an absence of streamflow routing routines. The use of STORM to establish "critical conditions" for pollutant loadings through long-term simulation is considered an inherently suspect procedure. Determination of critical transient conditions on an *a priori* basis would require simultaneous simulation of a wide variety of factors (e.g., antecedent moisture and flow conditions, spatial pattern and timing of rainfall) over the entire drainage area of the water body in which problems occur--which is well beyond the scope of STORM.

Environmental Synthesis Techniques

Environmentally-based community and regional planning has received increasing attention in the U.S. in recent years. It is therefore logical to consider ways in which water quality management planning might be linked to such activities, and specifically, to investigate the present relevance of methodologies which have been developed for purposes of comprehensive environmental planning. The common characteristic of these methodologies is that they attempt to synthesize multiple environmental objectives in order to develop an overall land use and public facility plan. Primary attention will be paid here to the "suitability mapping" approach, associated with the work of G. Angus Hills, Philip Lewis, and Ian McHarg. A brief historical account will illustrate the important aspects of this approach.

The early work of Hills, a soil scientist and physical geographer, was concerned primarily with biological productivity of land and water. A major objective of his land planning approach was to provide criteria for subdividing large regions into homogeneous units based on biologic capabilities. Utilizing several different classes of mapping units, Hills' approach involved evaluating the *capability*, *suitability*, and *feasibility* of land areas for agricultural production, forest production, wildlife production and management, and recreation. These three levels of evaluation were defined as follows:

> *Capability*: the inherent potential of the combined physiographic features (landform, ground and surface water, soil and climate) of an area for biologic production.

> Suitability: the capacity of the site in its present condition to respond to specific management practices (kind and degree of effort) for a particular use.
>
> Feasibility: the relative advantage of mapping, i.e., designating an area for specific uses having regard to its suitability for these uses under existing forecasted socioeconomic conditions.

These concepts were refined and brought to bear more specifically on urban growth by Philip Lewis, in his development of the "environmental corridor concept." The major objective was to define and evaluate the ability of resource patterns to be determinants of urban form. Planning would involve inventory, mapping, and overlay analysis of resource patterns involving above-surface, surface, and below-surface land conditions. Primary emphasis would be placed upon identification of areas which should be protected, particularly for purposes of recreation. A numerical rating system would be utilized in the identification process; prioritization of areas would be achieved by summation of the ratings based upon individual resource factors.

The concepts of suitability and compatibility have been developed most fully by Ian McHarg, in his book Design with Nature and later work. The two leading characteristics of McHarg's approach are: (1) a detailed description of existing ecological processes; and (2) a systematic analysis of land uses vis-a-vis natural land features using a compatibility matrix. Human and non-human life processes are evaluated and subsequently presented as limiting or liberating criteria for land development. The compatibility matrix then relates potential land uses to natural land categories, where the latter involve factors such as climate, geology, physiography, hydrology, soils, plant associations, wildlife, and unique sites. Each combination is rated, utilizing a broadly-based value system; and the findings are presented graphically in the form of composite suitability maps.

Recent environmental planning activities have tended to emphasize the data collection aspects of these approaches. Digitization of land characteristics, interpretation of satellite data, random point sampling, computer mapping, and other modes of data collection and manipulation have received increasing attention, particularly in studies which deal with large regions. Analysis of this information usually does not include full implementation of the suitability concept as outlined above. Typical activities are delineation of environmentally sensitive areas, according to accepted standards and criteria, and estimation of the aggregate environmental impacts of land use and land development, utilizing various assumed relationships.

Certain factors relating to the historical development of these environmental planning techniques may limit their appropriateness for current water planning studies. One issue is that suitability mapping and related approaches tend to be oriented toward a fundamentally different set of problems than are relevant in water quality management. Typically, comprehensive environmental planning must arrive at a set of land use recommendations on the basis of a wide variety of factors which are incommensurable and/or nonquantifiable. Thus, the structure of planning methodologies is strongly influenced by the need to provide a rational basis for definition and weighting of objectives. In contrast, the objectives of current water planning studies are relatively unambiguous. The constraints which must be met, and the degree of success which is attainable through various controls, are much more amenable to quantification than many other types of environmental impact (e.g., impacts on terrestrial ecosystems). This difference might not appear important, given the deterministic tone of many discussions of environmental planning, such as the following passage from Design with Nature (p. 56):

> "The formation of . . . environmental protection regulations requires no new sciences; we need move no nearer to the threshold of knowledge than the late 19th century. We can initially describe the major natural processes and their interactions and thereafter establish the degree to which these are permissive or prohibitive to certain land uses. This done, it will remain with the government and the courts to ensure our protection through the proper exercise of police power."

However, a wide variety of assumptions are clearly required to move from an analysis of natural processes--often very imperfectly known--to a specific land use plan. Many of the aspects of planning methodologies which are oriented toward making (or obscuring) these assumptions are essentially irrelevant to current water planning programs.

Another factor is that environmental planning methodologies have been influenced by the situation which exists for many terrestrial systems, in which land development is necessarily antithetical to environmental values. Preservation of woodland ecosystems, for example, can only be achieved through exclusion of development. Until recently, this has caused very heavy emphasis to be placed on the land use aspect of environmental protection, as opposed to the possibility of applying mitigative measures. Suitability mapping and related approaches can encompass the use of mitigative measures, but generally are not well-developed in this regard. In the case of water planning, however, mitigative measures are likely to be a dominant feature of recommended plans. Measures are available which can offset or prevent most water-related impacts of most types of land development, at most locations. Major attention must therefore be paid to design and evaluation of these mitigative controls, and to related activities such as establishment of appropriate performance standards. Comprehensive environmental planning methodologies are often not highly relevant to these tasks (with some exceptions such as the Christina Basin approach noted below).

It is felt that, with three major exceptions, land use control tends to be a secondary aspect of urban water resources protection. The three exceptions are: (1) control of land development with on-lot sewage disposal systems; (2) prevention of direct encroachment upon watercourses and wetlands; and (3) protection of important groundwater aquifers. Except for these cases, direct control of land use is a relatively inefficient means of achieving water-related objectives, due to the availability of other mitigative measures. By the same token, water-related objectives per se may not form a sufficient basis for establishing and defending land use controls. Thus, planning methodologies which are implicitly oriented toward land use control are appropriate primarily in communities where there is strong support for environmentally-based land planning, and where it is possible to link land use controls to a variety of objectives besides water. The value of such methodologies for regional water planning studies, encompassing many governmental units, tends to be limited. (These issues are discussed in greater detail in Section 8.)

A general comment regarding large-scale programs of land data collection is that techniques for data collection, manipulation, and presentation do not necessarily constitute a water planning methodology. Explicit linkages to the hydrologic system must be established in order to utilize such data for design and evaluation of water resources protection measures. A major problem is that the ability to collect and process land data tends to exceed the ability to establish reliable land/water relationships. In the design of planning programs, the existence of technical land/water relationships is sometimes treated as an afterthought; whereas this issue is crucial to the selection of variables, the appropriate level of spatial detail, and other aspects of land data collection. A second point is that implementation of at least some water resources protection measures for new development does not necessarily require comprehensive land data of any kind. For example, erosion/sedimentation controls can be enacted without detailed knowledge of the amount and spatial location of land in the study area having various erodibility characteristics--even if these characteristics are treated explicitly in the regulations. Analysis of particular areas of land, other than as necessary to demonstrate the general need for controls, could be deferred until the time at which specific development proposals are reviewed. This approach would not allow systematic prediction of erosion and sediment loadings, with and without controls, on a watershed basis; but such predictions are not always necessary. The purpose of this discussion is simply to suggest that: (1) land data requirements should be reviewed very carefully; and (2) collection of land information on a comprehensive basis need not be a dominant element of water planning studies. Such data can be extremely useful for a wide variety of planning purposes in addition to water resources protection; but these other purposes should be made explicit if they are important in justifying a given data collection program.

A somewhat unusual planning methodology which should be mentioned here was the approach utilized by the Water Resources Center at the University of Delaware, in preparing a plan for the Christina River watershed (Tourbier, 1973). This approach involved a very fine-grained analysis of the mitigative measures necessary to prevent deterioration of water resources due to land development at each point in the watershed. The cost of prevention of impacts was then computed for each prospective land use in each small area; and this was considered to be the critical determinant of feasible land use patterns. One potential limitation of this approach is that it does not deal with the problem of establishing appropriate performance standards for new development in cases where the "zero impact" concept is not applicable. (This may not be a serious difficulty when water quantity considerations are emphasized in the design of controls, as is recommended here.) A second issue is the extent to which it is actually possible to establish the cost of preventive measures on a generalized basis for small land areas. The least-cost control solution in a given case is likely to depend upon very detailed aspects of development design. The Christina Basin approach is considered to represent an important contribution to environmental planning, however, due to its emphasis upon mitigative measures and their relationships to land characteristics.

Statistical Techniques

Statistical analysis of empirical data can be utilized to estimate relationships between land characteristics and water quality for a given study area. Perhaps the most important aspect of multivariate statistical analysis is that it potentially allows the investigator to control for variables whose effects cannot be isolated in the data collection process. For example, suppose that the loading of some pollutant, Y, is related to urban land uses, X and Z (e.g., residential and commercial development). It might theoretically be possible to establish these relationships just by measuring pollutant loadings for basins containing only land use X, and basins containing only Z. However, when "pure" cases of X and Z are unavailable, the relationships can, instead be estimated through multivariate analysis of loadings (Y) for basins containing both X and Z in varying degrees. The inclusion of both as explanatory factors means that Z is controlled in estimating the relationship between Y and X; and X is controlled in estimating the relationship between Y and Z.

Statistical analysis can be useful for estimating relationships between water quality and hydrologic variables (e.g., relationships between pollutant concentrations and discharge, for various phases of the hydrograph). However, the present discussion will be limited to analysis of the influence of watershed characteristics. A general comment regarding the relative value of statistical analysis, versus other means of obtaining predictive relationships, is that the existence of error in equations obtained statistically is not a basic issue. All predictive relationships contain error; the distinguishing feature of statistical analysis is that error is treated formally, and is utilized as a criterion for accepting or rejecting relationships. Some of the important general aspects of statistical approaches have already been mentioned in the earlier discussion of stochastic versus deterministic modeling. The present discussion will pertain to: (1) the stringency of data requirements for statistical analysis; (2) the need for finesse and intuitive judgment; and (3) the usefulness of the predictive relationships obtained. The explicit focus is upon regression analysis, although most comments apply also to analyses of variance and covariance.

Data requirements for statistical evaluation of land/water relationships are severe, in that it is necessary to obtain comparable data for a relatively large number of catchment areas. These can consist either of individual basins, or of stream segments for which the incremental effects of land drainage have been isolated by upstream and downstream sampling (the latter data being less desirable due to the large percentage errors which are possible). The need for a substantial number of catchments relates to the statistical role of "degrees of freedom," a quantity which is equal to the number of observations minus the number of explanatory factors considered in a given equation (including the constant term). Statistically significant results can sometimes be obtained with very few degrees of freedom; examples exist in the water quality literature of regression analyses with as few as one degree of freedom (Radziul, *et al*, 1973). However, very rarely can equations be considered substantively significant, or usable for prediction, unless there are many more observations than variables. Ordinarily, the number of degrees of freedom necessary to obtain favorable results increases rapidly with the number of explanatory factors to be retained in an equation. The practice of artificially inflating degrees of freedom by including multiple water quality observations for a given catchment (so that values of the explanatory factors are repeated) may be legitimate in a statistical sense, but encourages overstatement of the reliability of the land/water relationships obtained.

The variables utilized in statistical analysis must all be measured in a similar fashion for all catchments considered, a requirement that is likely to involve substantial effort and may discourage investigation of any but the most general explanatory variables. Typically, much of the existing water quality data in an area will be found unusable for statistical analysis, due either to inadequate description of pollutant loadings (e.g., lack of discharge data, or lack of repeated sampling during storms) or the fact that water quality in the given catchment is influenced by factors that cannot be controlled adequately. Thus, collection of additional water quality data is likely to be necessary, as is typically true in the case of stormwater modeling.

The application of statistical tools to obtain realistic, usable relationships on the basis of observed data is a subtle process requiring considerable judgment. Beyond the need to establish statistical significance, and to avoid problems such as collinearity and heteroscedasticity, formal statistical theory provides relatively little indication of how to conduct a reasonable analysis. In fact, the most common abuse of statistical tools in non-experimental fields is over-reliance upon formal significance testing in the choice and specification of variables. This frequently leads to very unrealistic relationships. Statistical significance should be viewed as a necessary but not sufficient condition for inclusion of a given variable in a regression equation; many other criteria should be considered as well. In investigations dealing with land use and urban form, there is generally a high probability that statistical significance will be due to spurious associations or indirect linkages, rather than direct relationships. For example, personal income tends to be a good predictor of pollutant loadings from residential neighborhoods; but this is obviously not due to any direct physical linkage. Often it is best to view statistical analysis as a learning process, rather than a search for definitive relationships. The major outcome may in fact be to suggest the importance of factors which have not been explicitly measured. A skilled investigator may be able to achieve many of the same objectives through review of empirical data without statistical tools. These tools may be important primarily as a means of providing discipline when quantifying various effects.

As noted earlier, statistically-estimated land/water relationships tend not to be usable for direct evaluation of water quality controls, since they do not deal with pollutant sources at the level of specificity necessary for this purpose. Therefore, the greatest potential value of statistical analysis in water planning studies is to: (1) establish the relative importance of various aspects of pollutant generation; and (2) predict in-stream pollutant loadings at points for which direct information is unavailable. Achievement of the first of these objectives requires considerable sensitivity on the part of the investigator. It is unfortunately true that most statistical investigations of land-water relationships do not add greatly to existing knowledge. A significant aspect of statistical analysis is that it is implicitly an averaging process, as necessary to yield general relationships; but the most critical factors in water planning are often those influences which are relatively unique (or are otherwise unsuitable for consideration in statistical studies). An investigator may therefore be faced with a choice between: (1) focusing upon catchments in which the influence of site-specific factors is likely to be minimal, thus enhancing statistical explanation but obtaining equations that may not be widely usable for predictive purposes; or (2) analyzing a typical selection of catchments, and allowing the effects of site-specific factors to be attributed to general watershed variables such as imperviousness, population, and major types of land use. Such a dilemma tends to be involved in all methodologies for obtaining general land/water relationships.

The value of statistically-estimated relationships for predictive purposes depends upon the care with which they have been developed, and the extent to which prediction involves extrapolation beyond the conditions represented in the study sample. Empirically-based land/water relationships tend to be conservative, in that they usually do not predict extreme high and low values of water quality variables. This central tendency is considered a favorable characteristic, along with the fact that the relationships are a direct reflection of observed data.

On balance, it is felt here that the only urban water quality problem which is likely to be highly favorable for statistical studies is surface water pollution due to domestic on-site sewage disposal. Several relevant factors in this case are that: (1) in areas where on-site waste disposal is common, its influence on water quality can often be highlighted effectively through careful selection of sample catchments; (2) the water quality effects of on-site waste disposal are somewhat easier to characterize than is true for other urban pollutant-generation mechanisms; (3) the important explanatory factors are unambiguous and are not overly difficult to measure; and (4) the relevant control measures are well-known, so that the major needs are to estimate loading magnitudes, identify problem areas, and establish the general importance of controls. (Further discussion of such studies is presented in Section 10; one example is contained in Howard and Hammer, 1973.)

With regard to other aspects of urban pollutant generation, it is recommended that the use of statistical analysis be limited to estimation of very simple relationships. The relationships obtained would be used as predictive tools only in cases where it was clearly not feasible to obtain direct measurements of pollutant loadings. The primary uses would be instead to: (1) assist in partitioning observed pollutant loadings among source types; and (2) generate "baseline" pollutant loading values, as an assistance in identifying relatively high-yield areas within the study region. The latter function is related to an overall strategy for analysis of existing unrecorded pollution problems which is discussed in the next section.

Other Planning Methodologies

The other methodologies reviewed as part of the present study consist primarily of water planning tools which address highly specific problems. Those which have been selected for emphasis are discussed in later sections of this report. The overall viewpoint developed here is that, in dealing with unrecorded pollution problems other than combined sewers, agencies should generally avoid heavy commitment to specific planning methodologies until such time as the types and magnitudes of existing problems are at least roughly understood. The use of very straightforward analytical procedures may be adequate, especially in cases where planning resources are limited. When dealing with future urban development, the most important issue may be the selection of problems for emphasis, rather than the choice of planning methodologies. Given the overall approach recommended here in Section 7, there are a number of relatively simple methodologies which could fulfill the needs of current water planning studies.

SECTION 7

ANALYSIS AND CONTROL OF EXISTING PROBLEMS DUE TO UNRECORDED POLLUTANT SOURCES

Introduction

Water quality problems vary tremendously among urban areas of the U.S.; thus, it is difficult to generalize regarding the appropriateness of any given planning approach. The present section nevertheless attempts to develop an overall strategy for analysis and control of existing unrecorded pollutant sources, which may be potentially useful in areas where planning resources are limited and existing water quality problems are not well understood. The underlying rationale for this approach is outlined in the next few pages, followed by discussion of various technical issues.

As before, the emphasis is upon urban unrecorded pollutant sources other than combined sewers. It should be emphasized that "recorded" versus "unrecorded" pollution is a practical distinction based upon existing documentation and regulation of pollutant yields, not a physical distinction among source types (as is true for SRA versus non-SRA sources). A continuous point discharge, for example, can constitute an "unrecorded" source if the effluent is not covered by a discharge permit, or exceeds permitted amounts in terms of wastewater quantity or strength. A danger in planning studies is that such pollutant loadings can be attributed to "nonpoint" sources (e.g., on-site septic systems and street surface runoff) when nonpoint source loadings are computed as residuals. Another point to be mentioned is that the scope of permitting activity is likely to increase in the future, so that the balance of recorded and unrecorded pollution may shift.

The present context for control of unrecorded pollution in most U.S. urban areas could be described as follows. Although many of the governmental mechanisms needed for control already exist, and although there are some corrective measures which would entail little cost, the implementation of controls will generally not be an easy task. In the case of measures which require public expenditure, the most critical fact is that Federal funding is usually not available--at present--as a lever for implementation. This represents a fundamental difference from municipal wastewater facility planning. The intent here is not to disparage the goodwill of municipalities with respect to pollution control, but simply to point out that the funding issue, which is always important, is especially so at the present time, due to the unfortunate coincidence of water planning efforts with general stress upon municipal finance. Except for industrial enclaves, the municipalities in which unrecorded source control is most needed tend to be those which are financially most hard-pressed. In the case of controls which involve major private expenditure (or opportunity cost), the parties affected could well subject pollution control regulations to legal testing as well as other forms of challenge.

A second point is that, for a large proportion of urban unrecorded pollutant sources, the possibility of overcontrol is not a serious issue at present. The potential importance of pollutants from watershed surfaces and waste conveyance facilities has been established in the literature. Within the range of control which can feasibly be achieved in the near future, it is usually safe to assume that implementation of corrective measures will be desirable, if not actually required to meet specific water quality criteria. For example, removal of pollutants from streets and other impervious surfaces might not be necessary in a given case for prevention of organic pollution or nutrient enrichment; but the reduction thus achieved in heavy metals loadings would be desirable and potentially very important. Although little is known about the ultimate effects of heavy metals and other toxic materials in urban runoff, their presence in receiving waters must certainly be regarded as a liability. In addition, "housekeeping" measures involving watershed surfaces are often justified on grounds other than water quality alone. Similar arguments apply to measures such as sewer system maintenance. Thus, although planners must avoid control measures which are obviously ineffective and/or discriminatory, there is much more danger that too little will be done than that too much will be done.

In view of this set of circumstances, it is legitimate to question the relevance of traditional planning approaches when dealing with unrecorded pollution problems. One element of these approaches is the emphasis placed upon comparison of control alternatives in terms of cost-effectiveness. The discussion in the previous paragraph suggests that such comparisons may not be generally necessary, given the range of possibilities which presently exist. A related point is that formal comparisons and trade-offs of control alternatives are often not sufficiently accurate to be worthwhile. As discussed elsewhere, the urban stormwater models which have been designed for this purpose are weak at the "front end." Even if calibrated carefully, they do not actually establish where unrecorded pollutants are coming from--e.g., streets, versus parking lots, versus the great variety of other source areas and mechanisms which exist. Thus, although the model structure may theoretically allow simulation of a wide variety of pollutant-generation mechanisms, the models may in practice have substantial value only in dealing with end-of-the-pipe control measures, such as runoff storage and treatment options. Evaluation of other types of controls is likely to involve such questionable assumptions that the advantages of a complex methodological format are largely nullified. Partly for this reason, it is felt that trade-off analysis of control alternatives should be a major focus of attention only in cases where runoff storage and/or treatment for existing urban development is considered to be a serious possibility. An hypothesis offered here is that such cases presently do not include the bulk of urban land in the U.S. with separate sanitary sewers.

A general concern is that accepted water planning approaches tend to be oriented toward criteria which are essentially irrelevant to the task of establishing what is possible in terms of unrecorded pollution control. In contrast, the strategy suggested here is essentially a "bottom up" approach in which implementation feasibility is recognized as a dominant issue. Technical planning efforts would not be seen as attempting to develop a "best" plan according to any *a priori* criteria, but rather as a process of establishing a favorable set of controls and providing specific documentation for defense of these controls. The difference in emphasis is significant in that, due to the complexity of unrecorded pollution problems, activities conducted in pursuit of a "best" plan may not be particularly helpful either in pointing out the control possibilities which exist, or in defending the control plan which is ultimately recommended. The alternative is to stress direct examination of water quality problems, and documentation of pollutant sources at the same level of detail that is relevant for analysis of controls. Allocation of technical planning efforts among pollutant sources would be geared closely to the probability that a given item of information would affect control implementation. Additional aspects of this approach are discussed in the next sub-section.

An important issue regarding trade-off of controls has to do with the planning implications of transient water quality conditions versus conditions at low flow. Arguments have been made in the literature that transient problems may often be the more critical in urban areas, and that therefore direct substitutability exists between control of recorded effluent discharges and control of SRA pollutant sources. (Non-SRA unrecorded sources are ignored here for simplicity.) One comment is that, if water quality is to be maintained at desired levels during low flow, substitutability should not be a highly important issue in most instances. The hydrologic conditions requiring the most stringent control of municipal and industrial wastewater effluents are likely to consist of extreme low flow, regardless of the relative significance attributed to transient versus long-term conditions. (For a number of reasons, it appears unlikely that concern with transient problems will bring about higher levels of treatment for recorded effluents than are necessary to meet water quality criteria at extreme low flow.)

On the other hand, such arguments may imply that transient conditions place a limit on the level of water quality which can reasonably be required at low flow. Substitutability would then exist in the sense that, for any given degree of SRA source control, the treatment levels for recorded effluents could be adjusted so that transient water quality conditions and extreme low flow conditions were somehow equivalent in terms of constraint on water use. Since this would require adjustment of water quality criteria, the implication is that the criteria applied at low flow should be dependent upon the achievable level of SRA source control. This would mean that consideration of transient water quality conditions could erode the basis for advanced treatment of recorded effluents. Such a possibility appears to be precluded by current EPA regulations, but is nevertheless noted here as a potential danger. Given the present lack of knowledge concerning the significance of transient conditions, and the substantial probability that SRA pollutant sources will continue to be somewhat under-controlled in the near future, agencies should be skeptical of actions which could result in under-control of recorded effluents as well.

Trade-off between municipal and industrial discharge control, and control of unrecorded pollution, should not ordinarily be emphasized as an issue.

Selection of Problems for Emphasis

Given that the present discussion is concerned primarily with cases in which planning resources are relatively limited, the issue of allocation of resources is important. It is convenient when considering this question to divide planning activities conceptually into two categories: technical activities and promotional activities. "Promotional" refers in a very general sense to all activities oriented toward implementation of water quality controls, including the drafting and promulgation of recommended plans. It is clear that promotional efforts should be well-balanced, in that specific problems and solution measures should be given emphasis roughly in proportion to their perceived importance. Considerable latitude exists in the allocation of technical resources, however. The present discussion considers briefly the question of allocating technical resources among: (1) types of unrecorded pollutant sources; and (2) types of in-stream water quality problems.

Perhaps the most important issue with regard to pollutant sources is the extent to which attention should be focused upon washoff of pollutants from street surfaces. When considering any pollutant source in the present context, the relevant criteria for allocation of technical effort would appear to be the following: (1) the relative importance of the source in terms of loadings; (2) the amenability of the source to control; and (3) the likelihood that technical planning efforts will make a decisive difference to implementation of controls. Street surface washoff clearly ranks high in terms of the first criterion, although the very heavy emphasis upon street surfaces in the literature as the origin of urban runoff pollutants may be somewhat unjustified. It is felt, however, that street surfaces rank relatively low in terms of the other two criteria. Control of the problem through street sweeping is hampered by the relatively low efficiency of most sweeping equipment, the problem of parked cars, the generally poor state of municipal finance, and the fact that this measure is most needed in communities which can least afford it.* End-of-the-pipe measures tend to be limited by the great expense of installing runoff storage facilities in existing neighborhoods. With regard to the role of technical research in encouraging implementation, it is likely that communities will intensify their street sweeping programs and other housekeeping activities voluntarily, or not at all. For a variety of reasons, technical inputs other than general descriptions of the problem are not expected to exert a great deal of leverage.

Thus, given any reasonable weighting of the abovementioned criteria to form an overall index, it is felt that street surface pollutants would rank relatively far down the list of unrecorded pollutant sources, as a focus of technical planning activity. The resources allocated to this subject would then depend upon an agency's perception of its importance relative to the overall level of pollutant reduction which can or must be achieved. If street surfaces are thought to account for 75% of unrecorded pollutant loadings, and if the minimum acceptable reduction in total loadings is 50%, then street surface runoff obviously should receive a great deal of attention; but it is not clear that such a case would be typical. The recommended approach in most instances is therefore to encourage municipal housekeeping measures strongly in promotional activities, but to minimize the investment in technical backup for these measures (many of which, such as improved garbage collection practices and general cleanup operations, cannot be evaluated quantitatively in any case). With regard to street surface contaminants *per se*, it is suspected that, although this problem is not uncontrollable, the most important gains in the long run will be achieved by change in the pollutant-generating characteristics of motor vehicles, improvement in air quality, and change in personal habits, rather than by removal of pollutants once present on street surfaces.

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* Given the "gap" in municipal services which is often felt to exist in central cities, it is interesting to speculate upon the reactions of ghetto residents when their streets are forcibly cleared of cars and swept for the fourth or fifth time in a given month.

Finally, one overall problem created by emphasizing street surface pollutants is that it reinforces the view that "everyone is responsible" for pollution problems. This view is partially valid, although some are more responsible than others. The difficulty is that this view could have a generally debilitating effect upon implementation of controls. There are a number of arguments, some perhaps cynical, for focusing at the present time upon the "bad guys"; this could be viewed explicitly as an interim tactical approach. It is felt that these localized influences can be shown to constitute a large proportion of unrecorded pollution in many areas, if agencies take the steps necessary to document their existence.

The major issue regarding selection of water quality problems for analysis is the extent to which attention should be focused upon transient water quality problems, which occur during and immediately after surface runoff events, as opposed to long-term problems. The latter are defined as water quality conditions, produced by SRA sources, non-SRA sources, and/or recorded effluent discharges, which can be observed during some or all periods of steady-state flow. Transient water quality problems due to urban runoff are generally limited to the following: (1) the direct effects on aquatic biota of temporarily high concentrations of toxic materials; (2) the effects of temporary dissolved oxygen depletion on aquatic biota; and (3) limitation of water uses involving human contact due to high pathogen concentrations following storms. Obviously, the extent to which transient problems must be considered depends upon their scope and magnitude in a given study area. Several general comments can be offered, however.

1. Except possibly in the case of pathogens, an integral aspect of water quality planning on the basis of transient conditions is to recommend appropriate standards for receiving water bodies, as well as to indicate how these standards can be met. The reasons are that: (a) the water constituents other than dissolved oxygen which are relevant to transient biologic impact are generally not covered by existing stream standards; and (b) the standards which exist have virtually always been established through reference to steady-state conditions, and may not be appropriate for control of dynamic conditions. Therefore, if transient chemical phenomena are considered, it

is necessary to deal at a fundamental level with their importance--specifically, their impacts on aquatic biota--as well as to establish the existence and magnitudes of such phenomena.

2. A very slender base of information exists upon which to establish the biologic importance of transient pollutant loadings. Bioassay research has dealt almost exclusively with time intervals of several days or more (e.g., 96 hours). Few, if any, attempts have been made to simulate directly the biologic stress produced by stormwater, which may involve important interactive effects among pollutants. (These issues are dealt with in considerable detail in the Technical Appendix to this volume.) Given the critical relationship of water use to aquatic life, the general lack of biologic research in support of urban water planning studies is considered remarkable.

3. It goes without saying that organic loadings in stormwater, expressed as oxygen demand, are important only to the extent that transient oxygen stress is in fact produced. If oxygen is not affected significantly, for whatever reason, these loadings are not an appropriate planning parameter. Evidence suggests that organic loadings from urban land without combined sewers are not necessarily problematic; and that transient oxygen problems in general are extremely dependent on receiving water characteristics. The optimal conditions for transient oxygen depletion involve a light, localized rainfall which delivers a "first flush" of pollutants to a receiving water body which is already in marginal condition and for which the reaeration rate is low--followed by a period of one or more days in which little additional dilution is received. These conditions are most likely to occur in an estuary or standing water body during a period of generally dry weather. They are considerably less likely to occur in a free-flowing stream.

Due to these and other factors, it is felt that agencies should generally attempt to minimize the resources devoted to direct analysis of transient water quality problems. That is, (1) agencies should not assume that such problems exist, especially in the absence of combined sewers; and (2) major efforts should not be devoted to dynamic receiving-water analysis unless the importance of transient conditions can be established through direct observation (as opposed to simulation). A determination that transient problems need not be a major focus of attention, for part or all of a given study region, has potentially far-reaching implications for technical planning efforts, since it means among other things that stormwater modeling is probably not necessary.

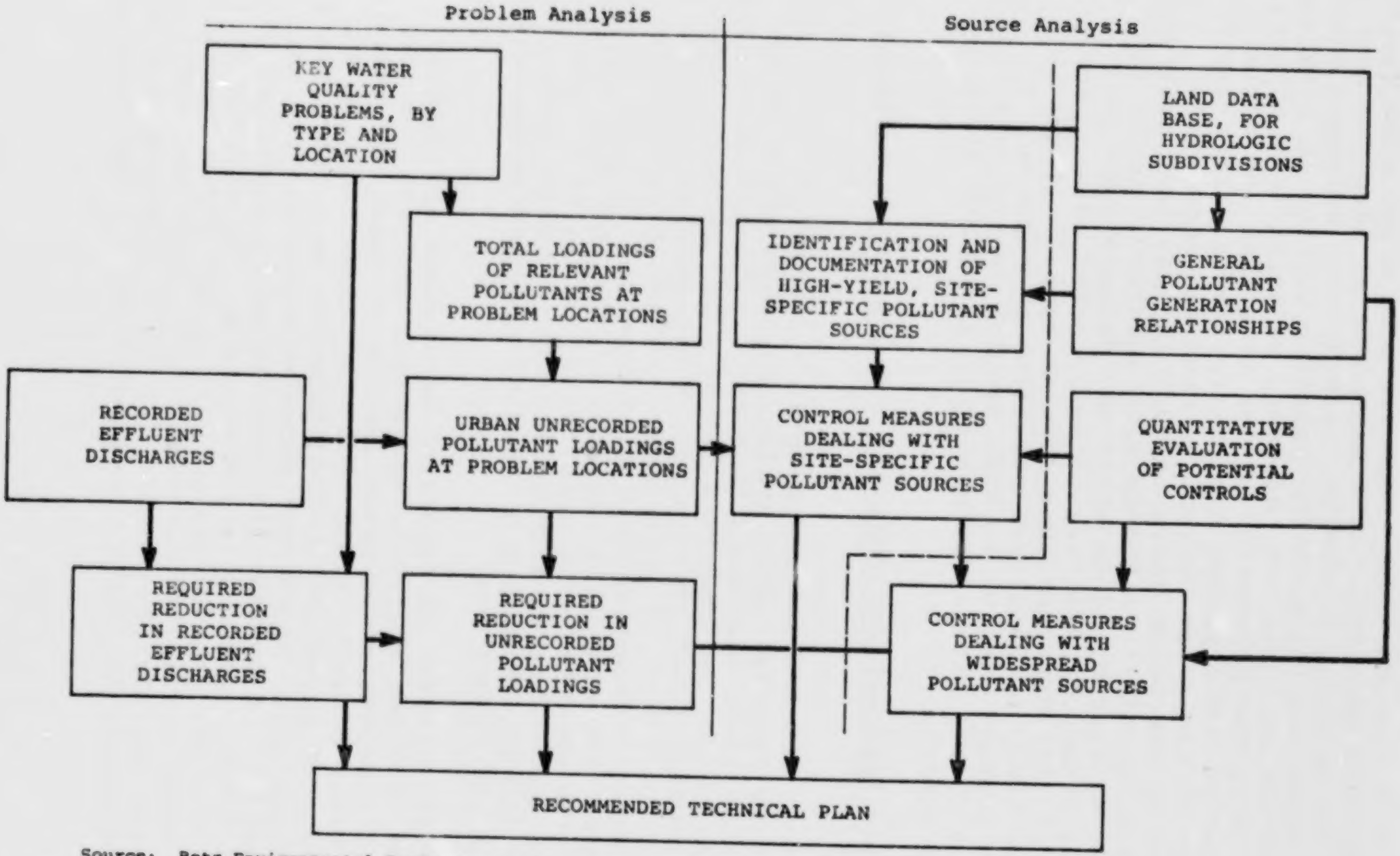
This view applies to transient water quality problems, not transient pollutant generation. Clearly, any quantitative analysis of SRA pollutant sources must deal in some fashion with short-term loading rates, and their relationships to discharge and other factors during storm events, if only for the purpose of computing long-term loadings accurately. The above suggestion applies only to the direct effects of transient loadings on water use, when analyzed for individual storm events. A second comment is that all influences on water quality exerted by benthic material (other than benthic material which is resuspended during periods of high discharge) are considered here as "long-term" problems, due to the fact that benthic influences persist after the direct runoff from a given storm has been flushed from the surface water system. The distinction between transient and long-term problems is admittedly arbitrary in some instances, but is very significant in terms of the manner in which problems are described and analyzed.

Even when the critical conditions for a given problem clearly occur during storm events, it may be adequate in some instances to avoid dynamic receiving-water analysis by employing long-term descriptions of the problem. For example, suppose that monitoring of a given water body indicates that the concentration of some toxicant exceeds a critical value in one day out of every five, corresponding to days in which rainfall occurs. This information would be adequate to establish that a problem exists, and that SRA pollutant sources are at least partially responsible. Suppose also that: (1) the total loading of the given toxicant at the problem area in question can be computed for a typical year or season; (2) the portion due to unrecorded sources can be estimated (as a residual); and (3) additional monitoring activities establish the existence of one or more specific SRA sources of the toxicant which account for disproportionately large shares of the total unrecorded loading (i.e., produce very high yield on a per acre basis). It is believed that this could represent an adequate base of information on which to design, defend, and implement control measures dealing with the specific sources in question. This information would not, however, be sufficient to estimate reliably the percentage of the time that the toxicant concentration would exceed the critical level after implementation of the given controls. Even the reduction in loadings, at the point where the problem has been observed, might be difficult to estimate with accuracy, due to the uncertain efficiency of controls and perhaps questions involving transport/delivery of pollutants. The appropriateness of this approach thus depends upon: (1) the relative importance of localized pollutant sources, and (2) the issues discussed earlier in this section regarding development of a "best" plan and the need to trade off different forms of control.

A Possible Approach for Analysis and Control of Existing Problems

The present sub-section outlines at a conceptual level an approach to remedial water quality planning which incorporates the ideas discussed thus far. This approach represents what might be done in a "worst case" planning situation, in which funds are limited, water quality problems are diverse, the nature of unrecorded sources is largely unknown, and the recommended plan is expected to face serious challenge. The essential elements of the technical planning problem are represented schematically in Figure 6. The focus is upon urban unrecorded pollutant sources generally; SRA and non-SRA sources are not distinguished except where noted in the discussion.

Two overall classes of technical activities are distinguished: problem analysis, and source analysis. A more balanced representation would include at least one additional class of activities, involving identification and evaluation of potential control measures as a third class. Problem analysis, based upon observed water quality data, is considered to be perhaps the most important technical element of current water planning studies. The outputs of this element include the following: (1) quantitative description of key water quality problems, by type, location, and relevant water quality parameters; (2) total loadings of relevant pollutants at problem locations; and (3) net loadings


Problem Analysis
Source Analysis
KEY WATER QUALITY PROBLEMS, BY TYPE AND LOCATION
TOTAL LOADINGS OF RELEVANT POLLUTANTS AT PROBLEM LOCATIONS
RECORDED EFFLUENT DISCHARGES
URBAN UNRECORDED POLLUTANT LOADINGS AT PROBLEM LOCATIONS
REQUIRED REDUCTION IN RECORDED EFFLUENT DISCHARGES
REQUIRED REDUCTION IN UNRECORDED POLLUTANT LOADINGS
LAND DATA BASE, FOR HYDROLOGIC SUBDIVISIONS
IDENTIFICATION AND DOCUMENTATION OF HIGH-YIELD, SITE-SPECIFIC POLLUTANT SOURCES
GENERAL POLLUTANT GENERATION RELATIONSHIPS
CONTROL MEASURES DEALING WITH SITE-SPECIFIC POLLUTANT SOURCES
QUANTITATIVE EVALUATION OF POTENTIAL CONTROLS
CONTROL MEASURES DEALING WITH WIDESPREAD POLLUTANT SOURCES
RECOMMENDED TECHNICAL PLAN

Source: Betz Environmental Engineers, Inc.

Figure 6 TECHNICAL PLANNING ACTIVITIES RELEVANT TO EXISTING UNRECORDED SOURCES

at problem locations due to urban unrecorded sources (obtained as residuals). Reference is made to "key" water quality problems because of the fact that it may be advantageous and/or necessary to be highly selective when choosing in-stream problems for intensive analysis. Selectivity applies to both the receiving water locations and the types of problems which are considered. In the case of location, the objective is to focus upon those points for which control of existing water quality problems would necessitate the greatest reduction in pollutant loadings. The selection process is analogous to finding the oxygen sag point when analyzing recorded discharges under steady-state conditions; but for a variety of reasons it is potentially much more complex. (One general difficulty is that the most critical problems tend to occur in those water bodies for which analysis is most complicated, due to multiplicity of pollutant sources.) In the case of water quality problems, and associated chemical constituents, selectivity involves deemphasis of problems which are: (1) relatively unimportant; or (2) secondary in terms of the required stringency of control. As an example of the latter criterion, a water body might be affected both by sedimentation and nutrient enrichment; but analytical attention might be focused only upon the latter problem, if it is judged that control of nutrient loadings will necessarily entail adequate control of suspended solids.

Estimation of pollutant loadings and concentrations at problem locations is distinguished in Figure 6 from analysis of the problem per se, in order to emphasize that the two activities are not necessarily the same (unless a given pollutant is defined to be a problem by existing water quality criteria). Two important points in this regard are that: (1) the investigation of problems can properly include a much wider variety of evidence than chemical analysis of water quality (examples are analysis of benthic materials, aquatic communities, and the tissues of aquatic organisms); and (2) the descriptions of water chemistry which are most relevant for problem assessment tend to consist of pollutant concentrations, whereas linkage to sources requires description in terms of loading rates. The need to analyze loading rates as well as concentrations is discussed later in this section, along with various issues involving measurement of loadings. In general, it is felt that the loading rates used in problem analysis should be descriptive of long-term conditions unless it is very clear that transient events are the dominant influence on water quality.

Source analysis, depicted in the right-hand portion of Figure 6, also involves measurement of pollutant loadings. However, the points at which such measurements are made typically do not coincide with the key locations for problem assessment, due to the emphasis in source analysis upon isolating the pollutant yields of particular unrecorded sources. It is emphasized again, with regard to analysis of unrecorded pollutant sources, that such analysis must deal with all influences on water quality other than effluent discharges currently specified in discharge permits. Any source mechanisms can be involved; and the relative importance of different source mechanisms should not be prejudged.

As indicated in Figure 6, source analysis involves three types of activities which logically precede the design and evaluation of controls. These are: (1) preparation of land data relevant to unrecorded pollution; (2) estimation of general pollutant-generation relationships; and (3) identification and documentation of specific pollutant sources. These activities involve a categorization of unrecorded pollutant sources along the lines suggested by earlier discussion of site-specific versus ubiquitous pollutant generation factors. It is hypothesized that, except for core districts of major cities, and other areas with combined sewers, the highest per-acre pollutant yields tend to be associated with site-specific conditions (e.g., dumping, sewer leaks, unauthorized discharges, handling of unusual materials) rather than simply reflecting variation in ubiquitous factors such as traffic and littering. Even if the high-yield sources are associated with land uses that are widespread in an area--e.g., manufacturing, petroleum wholesaling and retailing, trucking operations--they tend to be site-specific in that only a minority of establishments of a given type are actually involved. Site-specific sources are thought to be generally propitious for technical analysis since these sources tend to be relatively amenable to control once identified, due to the moderate public expenditure required in many cases, and the frequent existence of precedents and linkages to ongoing programs. Thus, detection and documentation of specific sources is distinguished from investigation of the overall pollutant-generation characteristics of urban land. Although the former activity may lead to controls which apply to more than one location, the important characteristic is that the design and defense of these controls is based upon analysis of highly specific cases.

The development of pollutant-generation relationships includes any activities which relate pollutant loadings to land use, imperviousness, population, employment, or other general characteristics of urban land. These activities can be oriented toward three overall objectives: (1) prediction of pollutant loadings at problem locations; (2) evaluation of the potential effectiveness of control measures; and (3) determination of baseline levels of pollutant generation for use in reconnaissance studies (discussed below). A general problem is that pollutant-generation relationships tend either to be unreliable, or to omit important site-specific pollutant sources (due to the characteristics of study areas upon which the relationships are based). Also, as noted earlier, relationships based upon monitoring of small catchments may not be directly applicable for prediction of pollutant loadings in major watercourses, due to factors involving pollutant delivery. These are reasons why the use of pollutant-generation relationships for prediction is considered inferior to direct measurement of pollutant loadings at problem locations, even though unrecorded loadings must typically be obtained in the latter case as a residual. With regard to evaluation of controls, a characteristic of pollutant-generation relationships noted earlier is their limited usefulness for analysis of land management measures (as opposed to end-of-the-pipe measures) due to failure to deal with land use at the required level of specificity.

Thus, agencies might not attempt to characterize pollutant generation on a comprehensive basis, except in a very simple fashion. The objective of this strategy in terms of data collection would be to minimize expenditure of resources in collecting "intermediate level" data--i.e., information which does not directly pertain either to key receiving water problems, or to pollutant sources at the level of detail needed to evaluate controls. Referring again to Figure 6, technical planning efforts would be devoted primarily to the items situated to the left of the dashed line. Control measures dealing with ubiquitous factors such as street dirt would be formulated and actively promoted as part of the plan; but only limited efforts would be devoted to quantifying pollutant generation due to these factors, and estimating the effectiveness of proposed controls. On the other hand, the effectiveness of controls for site-specific sources could often be estimated with considerable accuracy, due to the nature of these sources and the documentation which would be provided.

As indicated by the left-hand side of Figure 6, it is assumed that required treatment levels for municipal and industrial effluents can be determined more or less independently, relative to the process of establishing controls for unrecorded sources. Two relevant points from previous discussion are that: (1) extreme low flow will usually constitute the limiting condition for design of continuous point source controls; and (2) consideration of transient, storm-related problems should ordinarily not affect the stream standards that apply at low flow. An additional factor is that industrial treatment levels may be largely predetermined. Thus, the major issue is the extent to which unrecorded sources contribute to problems at low flow which serve as the basis for design of municipal effluent controls. This issue could involve pollutant loadings from SRA sources as well as non-SRA sources, insofar as the former are retained in local surface waters through deposition in benthic deposits and other mechanisms. The cases which would appear most relevant in terms of trade-off with municipal treatment levels would be: benthic oxygen demand and benthic BOD loads, due to pollutants from SRA sources; and nutrient loadings, involving both SRA and non-SRA sources. A more complete version of Figure 6 would thus perhaps show a mutual interaction between unrecorded source control and recorded effluent control in these instances. However, only in the case of nutrients is it felt that such interaction might justify major efforts to develop comprehensive predictive equations for unrecorded loadings (still assuming that combined sewers are not present). These equations would apply primarily to nutrient loadings from agriculture and domestic on-site sewage disposal.

To complete the steps shown in Figure 6, the total allowable pollutant loadings at each problem location would be determined on the basis of problem assessment and the magnitude of existing loadings and concentrations. Given the recommended treatment plan for recorded effluents, the required reductions in unrecorded pollutant loadings could be established (typically using descriptions of loadings which acknowledge variation due to hydrologic conditions). The extent to which these reductions exceed the expected abatement of site-specific sources would indicate the need for more general control of urban unrecorded pollution. As suggested above, major efforts would not be expended in attempting to gear the control plan for general unrecorded pollution sources to the required loading reductions, although estimates of control effectiveness would be prepared in some fashion.

An unavoidable problem with this approach is the difficulty of tracking down specific pollutant sources within a large study area. It is clear that some form of land data base and general loading relationships would be very helpful for this task (as well as for estimating loadings at problem locations which are not monitored directly). The objective would be to work back as efficiently as possible from problem locations to high-yield source areas. In order to execute this and other tasks, major watersheds would be divided into sub-basins, and ultimately into hydrologic subdivisions of perhaps one to five square miles each. The role of pollutant-generation relationships would be to indicate, on the basis of land data for a given catchment area, the pollutant loadings and/or concentrations which would be expected to occur under normal circumstances. These "baseline" predictions would provide a means of evaluating field data at each step, and selecting relatively high-yield areas for further attention. Very simple relationships could be utilized for this purpose. (An extreme case would be simply to select some variable such as population or impervious surface and use this as a divisor to "standardize" the data observed in the field.) An extended example of such a reconnaissance process, utilizing empirical relationships developed as part of the present study, is presented in the Technical Appendix.

In addition to activities such as just described, agencies may be able to select certain areas for monitoring on an *a priori* basis. Likely candidates are industrial districts and communities known to have deteriorating sewer systems. Regardless of the manner in which high-yield areas are identified, it becomes necessary at some point to conduct on-site inspection of streams and potential unrecorded pollutant sources, followed by highly selective monitoring of the latter (which can potentially include permitted discharges, if these are not already monitored). Although one can argue that such activities are not appropriate for current water quality management studies, the viewpoint adopted here is that there will probably be no better time (or agency) for this task, and that unrecorded pollution often cannot be well understood without direct observation--even if only on a sample basis. It is well to remember that current hypotheses regarding unrecorded pollution in urban areas are based largely upon: data for catchments containing multiple sources, measurements of surface pollutant accumulation, and theoretical considerations. Little is actually known about precisely where the bulk of pollutants are coming from, in either typical or untypical situations.

Successful application of this approach requires (1) a convincing demonstration that a water quality problem exists, and (2) a demonstration that a specific source contributes a disproportionately large share of the pollutant loadings responsible for that problem. Notice that the latter demonstration may be very imprecise in the case of SRA sources, since a major proportion of loadings from a given source may not reach a given problem location. Thus, a convincing demonstration that a source is especially important may require that the long-term, at-source loading rate be at least 5 or 10 times as great, on a per acre basis, as the total loading received from urban land at the problem location. Such a differential is particularly necessary when source documentation involves direct monitoring of runoff from an impervious surface. Nevertheless, it is felt that such sources commonly exist in urban areas, and may account for very large proportions of unrecorded loadings, particularly in the case of water constituents other than organics, nitrate, and suspended solids. (This discussion does not apply to areas with combined sewers, for which fundamentally different approaches are likely to be necessary.)

A final comment regarding land data and pollutant-generation relationships is that, regardless of the planning approach utilized, there is ordinarily not a real need for collection of highly detailed urban land use data. One reason is simply that not enough is known about pollutant generation to utilize detailed land use information efficiently for predictive purposes. As already indicated, many of the most important effects of urban land are likely not to be captured by such data even if the relevant relationships are understood. Various empirical studies suggest that the maximum usable base of urban land information, other than data obtained from field inspection and specialized sources such as sewer plans, might consist of the following variables, measured for hydrologic subdivisions: population, impervious surface, employment, land use (acreage of land in 5 to 10 categories); and the age and sewerage of dwelling units. Socio-economic variables such as income could have value as predictors, but are generally difficult to interpret. As noted earlier, the case in which estimation of detailed predictive relationships is likely to be most useful is analysis of domestic on-site sewage disposal. In this case, however, the need for detail relates primarily to natural land characteristics such as soils, rather than to land use.

Estimation of Pollutant Loadings

Pollutant "loadings" refer here either to rates of mass flux per unit time, or to the total mass load over a given time period (e.g., a storm period or a season). Commonly, investigations of water quality problems focus upon pollutant concentrations rather than loadings, since concentrations are more directly relevant to water use and are the measure in which water quality criteria are normally expressed. However, loadings must be computed for purposes of source analysis, whenever it is necessary to net out the influence of one or more specific factors (e.g., municipal or industrial discharges) or to deal with SRA pollutant sources. The need to consider loadings as well as concentrations in current water quality management planning studies is directly implied by the requirement that pollutant allotments be developed.

The present discussion focuses upon the estimation of pollutant loadings for water bodies affected by SRA sources. The need to deal with non-steady-state conditions, highly variable pollutant concentrations, and extended time intervals makes this situation fundamentally different from analysis of pollutant loadings at base flow. It is assumed at present that the loading analysis will not involve extrapolation to "critical conditions" involving a specific design storm. In such situations, stormwater modeling would ordinarily be utilized (although it is possible that equal or greater accuracy could be attained through simple hand computations, based upon *ad hoc* assumptions). The objective instead would be to estimate total loadings over an interval such as a season or a year. This is appropriate when the direct linkages between storm period loading rates and water quality either cannot be quantified accurately, or can be expressed on a long-term basis. (As an example of the latter, it might be possible to determine that an average of, say, 25% of phosphorus inputs to a lake during summer storms are retained in the water after the storm period, and thus are available to promote overgrowths of aquatic flora.)

Some form of extrapolation is nevertheless required for development of long-term loading estimates, due to the fact that it is rarely possible to observe all of the relevant conditions directly. Loading estimation can therefore be viewed as a problem of statistical inference, in which it is necessary to consider the variability of the factors involved. In order to avoid confusion in the present discussion, the important variables are defined below. The assumed objective is to compute the total load of some pollutant (P) over a time interval which is T days in length. Instantaneous points in time within this interval are denoted by the subscript "i". It is assumed that the behavior of pollutant concentrations and stream discharge during the interval is completely characterized by the values of these variables at "n" equally-spaced points in time (where i = 1, ..., n, and n is an indefinitely large number). Since it is impossible to observe pollutant concentrations and discharge at all n points, the missing values must be implicitly assumed. Thus, the objective in choosing a computational procedure is to utilize a form which incorporates reasonable assumptions regarding the missing values.

Quantities Pertaining to Instantaneous Points in Time ("i")

Qi = stream discharge in cubic feet per second at time i

Ci = pollutant concentration in mg/l at time i

Li = pollutant loading rate in pounds per day at time i

$$Li = 5.4\ QiCi$$

Quantities Pertaining to a Finite Time Interval

T = length of interval in days

n = number of points in time necessary for complete characterization of pollutant loading behavior (i=1,...,n)

D = average discharge during interval (cfs)

$$D = \frac{1}{n}\ (Q1 + Q2 + \ldots + Qn)$$

A = discharge-weighted average pollutant concentration (mg/l)

$$A = \frac{Q_1C_1 + Q_2C_2 + \ldots + QnCn}{Q1 + Q2 + \ldots + Qn}$$

R = average pollutant loading rate (pounds/day)

$$R = \frac{1}{n} (L1 + L2 + \ldots + Ln)$$

P = total pollutant load during interval, in pounds

$$P = RT$$

or, $P = 5.4\ DAT$

As indicated by the last two formulas (which are equivalent), there are two basic approaches to the problem of estimating a pollutant load for a given time interval. One is to estimate the average loading rate (R, in pounds per day) and multiply by the number of days in the interval. The alternative is to compute an overall loading rate for the interval, using average discharge and the discharge-weighted average pollutant concentration (A); and then to multiply by the number of days involved. The significant difference is that in the latter case it is usually possible to utilize an estimate of average discharge, D, which is based upon more comprehensive information than obtained in the water quality sampling program per se. For example, if the interval in question is a summer season, average summer discharge could be computed from long-term gaging station records for either the given stream or a comparable nearby basin. The estimation of D in this fashion usually involves small errors relative to the overall error variance in loading estimates. Thus, the major issue in choosing between the two formulas for P is the relative accuracy with which R and A can be estimated.

For virtually all stream locations affected by SRA pollutant sources, instantaneous loading rates are much more variable over time than pollutant concentrations. Thus, when utilizing simple averaging methods to compute the total pollutant load, it is generally better to deal with A than R. That is, it is safer to assume that observed values of pollutant concentrations are representative of all values, than to assume that observed loading rates are representative. This is true whether or not storm periods are isolated from non-storm periods in the computations.

The most accurate methods of computing pollutant loadings take explicit account of association between pollutant concentrations and discharge. Observed values of C or L are related statistically, usually through logarithmic regression, to corresponding values of Q. The resulting relationship is then linked to a flow-duration curve (which indicates the proportion of the time that discharge is within given ranges, for the entire interval under consideration). This makes it possible to establish average conditions for the interval even if the observations at hand are known to be untypical in terms of discharge. Since the choice of C or L is immaterial in this approach, and since comprehensive discharge data are required in any case, further discussion will focus only upon the use of concentrations rather than loading rates.* It is important to recognize that the behavior of pollutant concentrations during storm periods is likely to reflect a number of factors, as follows.

1. Dilution. Continuous sources which discharge at a constant rate will affect in-stream pollutant concentrations by an amount which is inversely proportional to discharge. A less-than-full dilution effect may prevail for sources involving groundwater outflow.

2. Washoff. In the case of washoff of materials from impervious surfaces, the rate of pollutant transport to surface waters is largely dependent upon

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* When L is related by logarithmic regression to Q, the regression coefficient obtained for log Q is equal to unity plus the value which would have been obtained if log C rather than log L had been the dependent variable. R-square is almost always higher in the former case, but the standard error of the regression coefficient for log Q is the same in both cases.

the amount of material available for transport. The resulting pollutant concentrations should therefore be positively related to the time since previous rainfall (although the nature of this relationship may be uncertain), and should decline throughout the course of a storm as material is removed. Except for the initial "first flush" period, pollutant concentrations should be negatively related to the rate of runoff.

3. Erosion. The important characteristic of erosion in the present context is that pollutant loading rates are limited by the ability of rainfall to detach and transport particulate matter, rather than by the amount of material present. Two classes of erosion processes can be distinguished, corresponding to the two basic types of overland flow. Erosion associated with Hortonian overland flow (which occurs when the rainfall rate exceeds the soil infiltration rate) would affect pollutant concentrations throughout a storm, by amounts which are positively related to the rates of rainfall and runoff. Washoff of pollutants from impervious surfaces can behave in a similar fashion, when pollutants have accumulated to a considerable depth, or consist of coarse-grained particulate matter. The other category of overland flow, namely surface runoff due to progressive saturation of the soil, would tend to yield increasing quantities of eroded material as a storm proceeds. (Pollutant yields from sanitary sewer bypasses which are activated by inflow of groundwater might resemble loadings due to saturation overland flow.) On the whole, erosion processes are distinguished from washoff processes in that the resultant pollutant concentrations tend to be positively related to the rate of runoff, and unrelated or negatively related to time since the previous storm. Also, in cases where both washoff and erosion are operative (which include a majority of watersheds in urban areas), pollutant loadings due to erosion processes tend to occur later in a storm period than loadings due to washoff.

The purpose of the above discussion is simply to emphasize the complexity of the mechanisms whereby in-stream pollutant concentrations are determined. Except for very small urban basins which are clearly dominated by washoff, the behavior of pollutant concentrations over time should never be prejudged, either in conducting empirical studies or in applying stormwater models.

Returning to the loading estimation problem, if a pollutant concentration is linked only to discharge, the relationship obtained can be applied directly to compute expected concentrations for various ranges of discharge. Although a discharge-weighted average concentration could then be developed, the simplest way to obtain the total loading for the time interval in question is to compute a loading rate for each range of discharge, and then to multiply this by the percent of the time that discharge is within the given range, and sum over all discharge categories considered. Greatest accuracy is potentially obtainable when this procedure is carried out separately for different hydrologic conditions, e.g., steady-state conditions, rising stage, and falling stage. However, it may not be possible to partition the long-term discharge records accordingly in order to obtain the necessary flow-duration information. When pollutant concentrations are highly variable, meaning that great accuracy is not obtainable in any case, it may be adequate to utilize only a few discharge categories for these computations. Section 11 depicts a case in which an annual sediment loading was computed using only four categories. Further detail was not warranted, even though a large number of observations were available.

An alternative procedure which should be noted is that of estimating total pollutant loads for several discrete storm periods, on the basis of numerous samples in each period, and then relating these loads to precipitation variables in order to extrapolate to long-term loadings. (This is basically what is accomplished by STORM, when calibrated for a particular basin.) Although there may be some difficulty in defining storm periods for large watersheds, this procedure is basically valid. However, the number of storms monitored is rarely sufficient to allow critical examination of the influence of precipitation variables on loadings. The extrapolation process must therefore be either very simple, or based upon a priori assumptions. Given the potential dangers of the latter, it is felt here that procedures based on intensive monitoring of individual storms are not particularly advantageous for estimating long-term loadings. It may be better to spread the sampling program over as many storms as possible, in order to maximize the probability of capturing the full range of conditions which exist.

A general concern is the extent to which loading estimates are likely to involve random error and/or systematic bias. An important aspect of pollutant concentrations is that they tend to involve a substantial degree of random variation--i.e., variation over time which cannot be explained by variables such as discharge, time since start of storm, time since previous storm, and average intensity of precipitation. The variability of pollutant concentrations has been examined in the current study by analyzing the stormwater data obtained by AVCO for 15 urbanized basins in Tulsa, Oklahoma (AVCO, 1970; see Section 5). Table 8 presents a tabulation, based on these data, of the number of observations required to estimate the average concentration of a given constituent to a desired degree of accuracy and confidence. Accuracy is expressed in terms of a multiplicative factor, listed in the left-hand column. For example, suppose that 8 independent observations of storm runoff from a given basin are available, and that the mean BOD concentration observed is 9.0 mg/l. Table 8 indicates that there is a 75% probability that the true average BOD concentration is between 6.9 mg/l (= 9/1.3) and 11.7 mg/l (= 9(1.3)). Similar tables have been prepared using pollutant concentrations which have been adjusted to eliminate variation due to precipitation factors. However, the required numbers of observations are reduced by only 10% to 15% relative to the figures shown in Table 8.

Table 8 thus provides a general indication that large numbers of observations may be necessary, due to the extent of random variation, in order to characterize pollutant concentrations accurately. The Oklahoma basins were all small catchments (between 0.1 and 1.5 square miles); somewhat less variability would be expected for larger watersheds. Also, the required number of observations might be significantly reduced if composite sampling were employed. On the other hand, discharge-weighted average concentrations, which are more relevant for loading analysis, are somewhat more liable to error than unweighted averages. Another factor which should be noted is that single chemical samples do not necessarily represent accurately the total cross-section of

TABLE 8

NUMBER OF OBSERVATIONS REQUIRED TO ESTIMATE AVERAGE CONCENTRATIONS OF WATER CONSTITUENTS, BASED ON OKLAHOMA DATA

	Accuracy Factor	Confidence Level			
		50%	75%	90%	95%
BOD:	2.0	1	2	3	4
	1.7	1	2	4	6
	1.5	2	4	7	9
	1.3	3	8	16	22
	1.2	6	16	32	45
	1.1	20	56	114	162
COD:	2.0	1	1	2	3
	1.7	1	2	3	4
	1.5	1	3	5	7
	1.3	2	6	12	17
	1.2	5	12	24	35
	1.1	15	43	88	125
TOC:	2.0	1	1	2	3
	1.7	1	2	3	4
	1.5	1	3	5	6
	1.3	2	5	10	15
	1.2	4	11	21	30
	1.1	13	37	76	107
OKN: (Organic Kjeldahl Nitrogen)	2.0	1	1	1	2
	1.7	1	1	2	3
	1.5	1	2	3	4
	1.3	2	4	7	9
	1.2	3	7	13	19
	1.1	8	24	48	68
OPR4: (Soluble Ortho-phosphate)	2.0	1	1	1	1
	1.7	1	1	1	2
	1.5	1	1	2	3
	1.3	1	2	4	5
	1.2	2	4	8	11
	1.1	5	13	27	38
SS: (Suspended Solids)	2.0	2	3	6	9
	1.7	2	5	11	15
	1.5	3	9	18	25
	1.3	7	21	42	60
	1.2	15	43	87	123
	1.1	53	155	316	448

Source: Computed from statistical analysis of data for 15 urbanized basins in Tulsa, Oklahoma (AVCO, 1970). See Technical Appendix.

flowing water in a stream. For example, Colston (1974, pp. 55-56) found that pollutant concentrations near a stream bottom may be systematically higher than surface concentrations.

A circumstance which is important to consider, since it occurs frequently in research studies, is the use of unweighted average concentrations instead of discharge-weighted average concentrations when computing total loadings. This procedure clearly tends to produce unfortunate results when storm periods are not isolated from nonstorm conditions; but it is sometimes adequate when storm periods are treated separately.* Considering just storm conditions, three types of situations theoretically can occur: (1) pollutant concentrations are uncorrelated with discharge (over all points "i" in a typical series of storm periods); (2) pollutant concentrations are significantly related to discharge, and the observations available for computation of loadings are randomly distributed over time; or (3) concentrations are significantly related to discharge, and the available observations are non-random. In the first case, a simple average of pollutant concentrations represents an unbiased estimate of the discharge-weighted average, so that there is no problem in using an unweighted average as an estimate of "A" (see above). In the second case, use of an unweighted average will impart a bias to the loading estimate obtained; but the bias may not always be serious.

Storm-period pollutant concentrations in urban watersheds frequently bear very mild overall relationships to stream discharge, due perhaps to the offsetting influence of washoff and erosion processes. For example, in Colston's study of a 1.67-square-mile watershed in Durham, exponential relationships between concentration and discharge were estimated for 19 constituents (Colston, 1974, p. 59). The discharge exponents obtained were between 0.15 and -0.15 for all constituents except suspended solids, cobalt, iron and calcium. (Similar findings were observed for the Pennsylvania watersheds analyzed in the current study; see the Technical Appendix.) As observed elsewhere, concentrations were negatively related to time since start of storm, meaning that a higher concentration would be associated with a given discharge during the rising stage of the hydrograph than during the falling stage. However, it is apparent that, if water-quality samples are representative of the full range of storm-period conditions, unweighted average pollutant concentrations may be fairly close to the discharge-weighted averages for most constituents. If the discharge exponent for a constituent concentration is 0.15 in a watershed exceeding one square mile, the unweighted average concentration would be biased downward by at most about 20% relative to the discharge-weighted average; and the upward bias should similarly not exceed about 20% if the exponent is -0.15. It is risky to assume that bias will always be within this range, however, particularly when dealing with water constituents other than organics and nutrients.

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* Isolation of storm and nonstorm periods can be accomplished by a variety of methods, ranging from formal base flow separation techniques to simplistic assumptions. Pollutant loading estimates do not appear to be highly sensitive to the methods used, as long as both storm and nonstorm loadings are ultimately considered, and as long as storm periods include nearly all nonsteady-state conditions. (The definition and significance of snowmelt conditions have not been considered here.)

Very serious errors can result in the third case mentioned above, in which pollutant concentrations are strongly related to discharge, and the observations available do not provide a balanced characterization of storm periods. A matter of particular concern here is that sampling programs frequently under-represent major storms, and streamflow recession periods generally, due either to preoccupation with first-flush effects or to logistical considerations. The result can be serious overestimation of pollutant loadings on a long-term basis.

A good example of this problem is the computation of annual lead loadings from Lodi, New Jersey, presented by Wilber and Hunter (1975). The average lead concentration observed in storm runoff from two small basins in Lodi was 0.90 mg/l. This figure was multiplied by runoff from Lodi as a whole to yield an annual loading. An interesting aspect of the observed lead concentrations was that they pertained entirely to light rainfall events. More than half of the storms sampled involved less than 0.1 inch of rain, and the maximum was 0.26 inches. In order to examine the significance of this circumstance, the published data have been subjected here to a regression analysis in which the average lead concentration for each storm event is related to the amount of precipitation (and a dummy variable distinguishing the two basins). The estimated equation is the following:

$$L = 0.237\ KP^{-.35}$$

where: L is average lead concentration for a given storm event, in mg/l

P is precipitation, in inches; and

K is a constant equal to 2.614 for basin 1 and 1.00 for basin 2.

Both independent variables are significant at 5%; R-square is 0.88. In this case, lead apparently bears a very strong negative relationship to precipitation, and presumably also to discharge. As an indication of the extent to which the 0.90 mg/l concentration may be inappropriate for estimating annual loadings, Table 9 shows the computation of a precipitation-weighted average concentration, using the above equation and a realistic rainfall distribution (based on southeastern Pennsylvania). The weighted average lead concentration is 0.767 mg/l for basin 1, and 0.294 for basin 2, yielding an overall average of 0.53. The discharge-weighted concentrations would presumably be somewhat lower, since runoff volume tends to be an increasing proportion of rainfall volume.

The purpose of this discussion is simply to indicate that, when preparing long-term pollutant loading estimates, it is necessary to consider the full range of hydrologic conditions which exist.

TABLE 9

SAMPLE COMPUTATION OF PRECIPITATION-WEIGHTED AVERAGE LEAD CONCENTRATIONS FOR BASINS IN LODI, NEW JERSEY

Storm Magnitude (inches)	Distribution of Rainfall by Volume	Estimated Average Lead Concentration (mg/l) Basin 1	Basin 2
0 - 0.09	5.5%	1.770	0.677
0.1 - 0.29	13.5%	1.087	0.416
0.3 - 0.59	20.0%	0.818	0.313
0.6 - 0.99	24.0%	0.669	0.256
1.00+	37.0%	0.537	0.206
Weighted average:		0.767	0.294

Source: Based on data from Wilber and Hunter, 1975.

Preparation of Land Data for Loading Analysis

The watershed characteristics which are relevant for unrecorded pollution loadings can be categorized roughly as follows:

1. Areal measures of "land use" (e.g., residential land, industrial land, etc.)
2. Descriptive measures of land surface characteristics (e.g., impervious area, curb length)
3. Indices of human presence and activity (e.g., population, employment, traffic)
4. Direct measures of land management practice, (e.g., fertilizer application, pesticide use)
5. Indices of environmental conditions and waste management effectiveness (e.g., cleanliness, sewer system condition)
6. Measures of natural land features (e.g., slope, soil characteristics, drainage density)

The first two of these categories are likely to be overlapping, in practice, since "land use" tends to imply a specific physical condition of the land, and vice versa. Also, indices of human presence and activity, such as population, are often considered as measures of land use. With regard to the last category, natural land characteristics are relevant primarily because of interactions between land use and natural features, i.e., cases in which the pollutant loadings yielded by a land use are dependent upon the characteristics of the land on which it is located. With regard to urban land use, such interactions are important for: (1) pollutant generation due to on-site sewage disposal; (2) soil erosion from construction sites; and (3) the effects of hydrographic modification, as produced by urban areas with less than complete storm sewerage. Interactions are relatively unimportant in other cases due to the fact that conventional urban development tends to homogenize the landscape, thus eliminating the influence of natural features.

A very serious problem in analysis of loading relationships is the fact that comprehensive data can rarely be obtained for the fourth and fifth categories of variables listed above, namely measures of land management practice, waste management, and environmental conditions. If measured effectively, such variables would capture most of the important site-specific pollutant sources; but systematic collection of such data is infeasible for large areas. The necessary omission of these variables in cross-sectional loading studies is a major reason why such studies are not emphasized here.

A general comment regarding variables that express land use, physical land condition, and human presence and activity is that no one type of measure is logically superior to another as a predictor of urban pollutant loadings. Most of these measures are, in effect, surrogates for actual pollutant-generation processes. For example, the water quality impacts of street litter, or disposal of motor oil in storm sewers, could be attributed variously to the existence of streets, residential land use, population, motor vehicle use, etc. Thus, the selection of variables as predictors of unrecorded pollution should be based largely on practical considerations.

Areal measures of land use--e.g., acres of land in residential, commercial, and industrial use--have two major drawbacks for pollutant-generation analysis: (1) existing land use measurements vary widely in terms of the delineation of uses (especially the distinction between "developed" land and other land owned by a given establishment or resident), and the classification systems employed; and (2) areal measurements typically fail to provide a sufficient description of land use intensity. The first of these problems may not be relevant for a planning agency which intends to conduct a new data collection program. The second drawback can theoretically be overcome by creating sub-categories of land use. For example, residential land use involving a given housing type could be subdivided according to population density. This solution is regarded as relatively inefficient for present purposes. The recommended approach is instead to focus upon activity measures, plus impervious surface, and to utilize land use data primarily in a modifying role. Measurements of employment or impervious surface, for example, could be categorized according to the general type of land use involved.

It is usually convenient in water quality planning studies to partition the study region into hydrologic subdivisions, or sub-watersheds, for purposes of wastewater facility planning as well as analysis of unrecorded pollution. If these hydrologic subdivisions are no more than about 5 square miles in size (in developed areas) they can ordinarily serve as the basic data collection units for land information. However, areas within hydrologic subdivisions which differ in terms of sewerage should be distinguished where possible. Land served by combined sewers, land with separate sanitary sewerage, and land without sanitary sewerage facilities should be segregated and treated as separate data collection units. If such a partitioning is not possible for a given hydrologic subdivision (for example, if there are residential neighborhoods containing both sewered dwellings and houses with on-site disposal), all variables measured for that subdivision should be broken down by sewerage class using assumed percentage distributions.

Measurements of variables such as land use, population, employment, and impervious surface can consist of totals or averages for these land areas. Information pertaining to smaller areas may be needed in some instances to assist field investigations in isolating high-yield pollutant sources; but preparation of such data can be postponed until specific needs are established. On the whole, when dealing with unrecorded pollution from existing urban areas, it is felt that numerical summaries of information are generally sufficient for technical planning purposes. Although much of the information may be derived originally from maps and photographs, there may not be a strong need to prepare new maps as part of the study, other than overlays showing the location of streams, sewers, hydrologic subdivision boundaries, and specific high-yield pollutant sources. This point is mentioned because detailed mapping tends to be very time-consuming, and thus can absorb a major proportion of planning resources. The principal tasks for which it may be necessary to map numerous land characteristics over large areas are the following: (1) analysis of the environmental impacts of proposed wastewater management alternatives, especially secondary impacts in developing areas (i.e., growth stimulation due to sewer construction); (2) analysis of existing and future water quality problems due to on-site sewage disposal; and (3) analysis of problems due to agriculture. Mapping needs with regard to other tasks should be examined very critically, in order to minimize unnecessary expenditure of resources.

In the empirical investigations described in Section 5 and in the Technical Appendix, employment was found to be the best single predictor of urban unrecorded pollutant loadings. The reasons were presumably that economic activities tend to be the most critical sources of unrecorded pollutants, at least in areas resembling the basins studied, and that employment is the best overall measure of economic activity. Although employment is not ordinarily considered in this context, the use of this variable in generalized loading relationships has certain advantages. Employment is a relatively unambiguous measure which is defined similarly by most existing agencies; thus, data from a variety of sources can ordinarily be utilized. Although comprehensive employment information is ordinarily not available for areas smaller than municipalities, reasonably accurate estimates can be prepared for hydrologic subdivisions, with moderate effort, by utilizing fragmentary sources such as industrial directories, tax records, and telephone surveys of major employers. Existing data for municipalities, counties, and metropolitan areas can provide control totals.

The manner in which pollutant-generation relationships should be developed, if at all, depends upon the characteristics of the region studied, the availability of existing data, and the feasibility of conducting sampling programs for this purpose. In cases where such relationships are desired but resources are very limited, the following approach might be utilized. Long-term pollutant loading estimates would be developed for five to ten basins in the study area which contain primarily urban development with separate sanitary sewerage. If pollution due to on-site septic systems is a major concern, an independent study should be conducted to deal specifically with this factor. The basins would not contain major construction sites or recorded discharges, unless it was very clear that the loadings due to these sources could be subtracted out accurately. Various intensities of development would be represented, with at least one basin containing very low-density development (but not agriculture). Basin size could be variable, although all basins would preferably exceed one square mile and would contain at least some natural drainage channels (unless complete drainage alteration is typical throughout the urban area to be characterized). The possible inverse relationship between areal pollutant loadings and basin size would be kept in mind. Since the number of basins assumed here would be too small to permit multivariate analysis, the constituent loadings would be analyzed simply by plotting observed values, expressed as mass per unit area, against an overall urbanization index. The results obtained in the statistical studies mentioned earlier, which were highly consistent, suggest two versions of such an index which might be appropriate. These are:

$$U1 = I + 5E$$

$$U2 = P + 4E$$

where: U1 and U2 are urbanization indices;

I is the percentage of basin land covered by impervious surface;

E is employment per acre; and

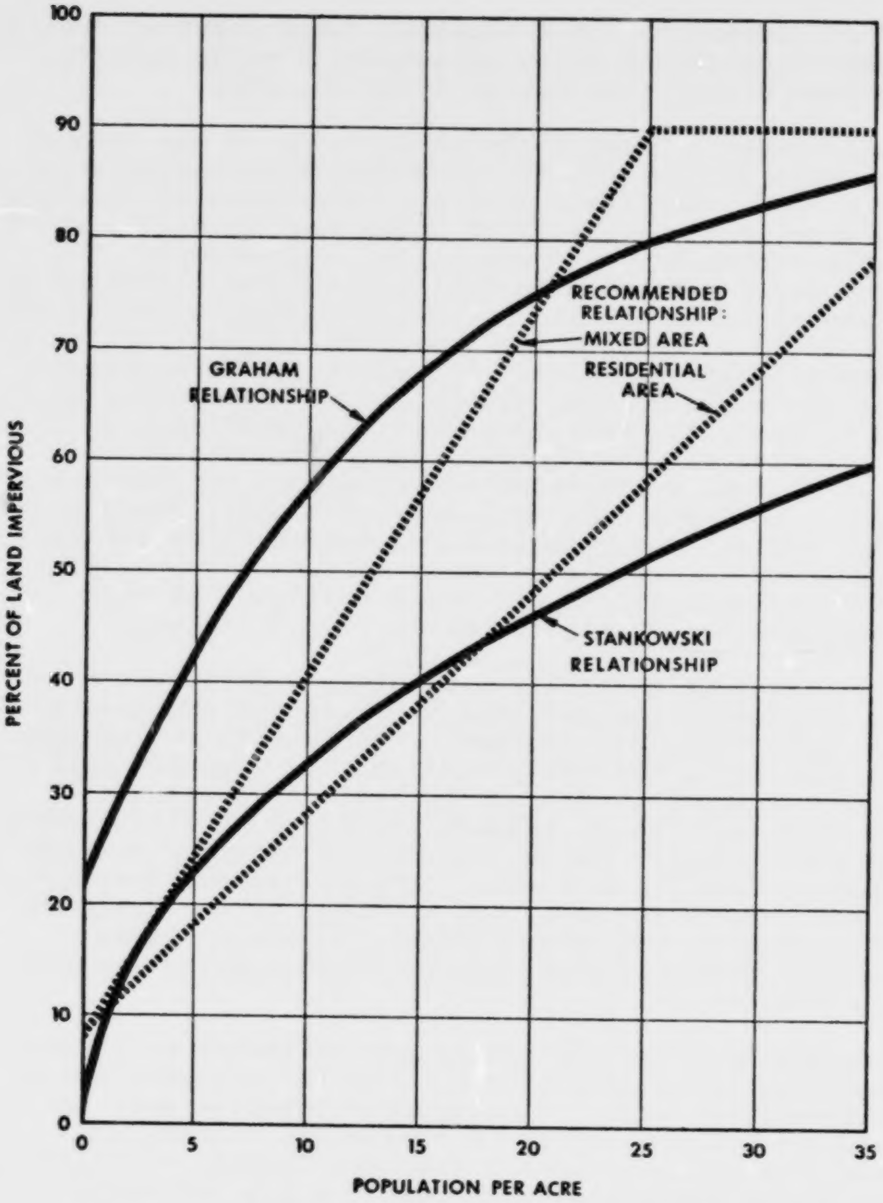
P is resident population per acre.

The relationship between observed loadings and either of these indices would then be usable for preparing very rough estimates of long-term pollutant loadings at other points in the surface water system. Such estimates could serve as a standard of comparison for evaluating field observations, or as a highly approximate means of assessing water quality problems when direct information is unavailable.

Some final comments concern the measurement of impervious surface, which is required in stormwater modeling as well as in other forms of loading analysis. Surprising differences tend to exist among estimates of impervious coverage, which may reflect differences in definition. For example, the Poquessing Creek watershed in Philadelphia was estimated to be 48% impervious in one study and 25% impervious in another study conducted at roughly the same time (Radziul, et al, 1973; Coughlin, et al, 1976). As understood here, impervious surface would consist simply of land covered by pavement and structures. Semi-impervious surfaces such as unpaved streets, railroad tracks, junkyards and unpaved parking lots might be included if prevalent; but all areas of uncovered soil would be excluded, even small areas such as highway medians and grass strips between curbs and sidewalks. However, it appears in many instances that either very different definitions are being employed, or that impervious coverage is significantly overestimated.

Impervious coverage generally represents a difficult measurement problem, since pervious surfaces and impervious surfaces tend to be interspersed. When aerial photographs are utilized, it is extremely difficult to identify impervious areas accurately, unless the scale is greater than 1:10000. The accuracy of methods utilizing satellite data (infared spectroscopy) is not known. In order to provide assistance in dealing with this problem, various investigators have estimated impervious coverage on the basis of population density and other characteristics of urban development. Several based on population density are presented in Figure 7.

The relationship by Graham (1974) was estimated by asymptotic regression using census tract data for the Washington, D.C., metropolitan area. Similar relationships were estimated linking imperviousness to employment density and household density. It appears that the Graham relationship tends to overestimate imperviousness for low and medium density development. A notable feature is that imperviousness is estimated at 22 percent for zero population density. (The corresponding intercept values for the employment and household relationships are 35 percent and 26



Source: Graham (1974); Stankowski (1974); Betz Environmental Engineers, Inc.

Figure 7 ESTIMATED RELATIONSHIPS BETWEEN IMPERVIOUSNESS AND POPULATION DENSITY

percent, respectively.) However, the 95% confidence interval estimated for the Graham relationship would include the other curves shown in Figure 7.

The Stankowski relationship was developed in a study of flood magnitudes in New Jersey (Stankowski, 1974). Estimates of imperviousness were obtained on the basis of land use data for 567 municipalities. These values were related to population density by polynomial logarithmic regression. The relationship obtained was the following:

$$I = \exp\ (2.265 + 0.573 \text{ in } P - 0.01695\ (\ln P)\ (\ln P))$$

where: I = manmade impervious cover, as a percent of total land area;

P = population density in persons per acre

An additional relationship, based on both population density and employment density, has been prepared as part of the present study. In this case, nonlinearity is expressed by a simple upper limit on imperviousness at 90 percent, rather than by an elegant functional form.

$$I = 8.0 + 2.0\ P + 3.2\ E, \text{ or } 90, \text{ whichever is lower,}$$

where I and P are as defined above, and E is employment density in persons per acre.

This relationship is illustrated in Figure 7 for two cases: a residential area with no employment, and a situation in which employment is equal to 0.4 times population. Use of this formula is recommended, either as an estimating technique or as a check on direct measurements, for urban land with at least 1 person per acre on the average (preferably 2). The accuracy is reasonably good when the areas considered are greater than 1 square mile in size.

For many purposes, especially the analysis of hydrographic modification, the most relevant variable is hydraulically-connected impervious area, rather than total impervious coverage. Hydraulically-connected surfaces are those which are directly linked to storm sewers or receiving waters by impervious channels. Determination of which surfaces are hydraulically connected can only be accomplished reliably by field inspection, although reasonably accurate guesses can be made from aerial photographs by a person familiar with development characteristics.

SECTION 8

IMPLEMENTATION OF CONTROLS FOR NEW URBAN DEVELOPMENT

Introduction

The present section describes briefly the various ways in which preventive water quality controls for new urban development can be implemented. For more detailed discussion, the reader is referred to the excellent report on this subject which has recently been prepared by Abt Associates (1976). The major focus here will be upon implementation of the measures which have been outlined in Section 4. The design of these controls will then be discussed in Sections 9, 10, and 11.

The term "control measure" is commonly used to refer to any actions which benefit water quality, ranging from construction of physical facilities, to legislative and administrative actions. In order to avoid confusion, control measures will refer here only to actions which directly affect the physical environment. The means whereby these controls are achieved are termed implementation mechanisms. This distinction is not entirely clear in some cases, but is generally useful in view of the fact that a wide variety of implementation mechanisms can often be utilized to achieve a given physical control.

Implementation Mechanisms for Preventive Controls

The following are the major categories of actions which are most frequently mentioned as implementation mechanisms for water quality controls affecting new urban development.

1. State Laws

   Two types of state legislation are potentially relevant: enabling legislation, and laws which directly govern the behavior of individuals and organizations. Enabling legislation tends to be most important, since a majority of the actions needed for control of unrecorded pollution are likely to be taken at the local level; and many of these actions may require amendments to zoning, subdivision, and construction codes which are not within the scope of existing enabling legislation. Direct action at the state level is most likely to involve problems which are important in rural as well as urban areas, such as water pollution due to on-site sewage disposal.

2. Local Ordinances

Numerous types of ordinances can be utilized at the local level for water quality protection. Some examples are erosion controls, special zoning ordinances, environmental impact statement requirements, and environmental performance standards. An important class of ordinances might deal with the management of potential pollutants such as fertilizer, pesticides, and residual petroleum products. A reasonable procedure in current water quality planning studies might be to examine first the extent to which the needed physical measures can be achieved through existing mechanisms (i.e., local government operations, subdivision review, construction codes), and to recommend separate ordinances only as necessary to supplement these mechanisms.

3. Municipal Operations

A significant proportion of municipal operations involving sanitation and public health are relevant or potentially relevant to pollutant generation. In many cases it may be possible to obtain major water quality benefits by changing or augmenting these operations without legislative action. Obvious examples would be intensification of street sweeping programs, catch basin cleaning, and general cleanup operations. (An issue which may be important is the extent to which municipalities can influence waste management practices on private property through enforcement of existing ordinances dealing with nuisances and vector control.) Significant benefits may also be achievable by expansion of licensing and regulatory functions to include sewer scavengers and others engaged in the handling of potential pollutants. On the whole, municipal operations could prove to be critically important in detecting and correcting site-specific pollutant sources.

4. Construction Codes

Amendments to construction codes may be utilized to minimize the impacts of new development on both quality and quantity of runoff. An extremely important action may be to upgrade construction codes dealing with waste conveyance facilities. Increased monitoring activities may be necessary to assure compliance with sewer construction codes once amended. Regarding impacts of new development on runoff quantity, there are a number of aspects of construction codes which affect the magnitude of this problem significantly, such as requirements involving roof drains, storm sewerage, elevated curbing, paved sidewalks, street width, and parking lot capacity for commercial establishments. Important benefits may be gained by reviewing existing codes carefully to determine cases in which they may be producing unnecessary impervious coverage or underutilization of the ability of pervious soil to absorb stormwater.

5. Operating Agreements

A serious problem confronting water quality control efforts at the local level is detecting and preventing surface pollutant accumulations and improper waste disposal practices on private property when there is not a clear nuisance situation or public health threat. In the absence of environmental ordinances dealing explicitly with these problems, it may be difficult to affect materials management in existing developed areas; but greater opportunities exist for establishing sound practices in new development. Whenever the granting of approvals for new development involves negotiation between developers and public agencies, it may be possible to include waste management as one of the issues under consideration. Measures such as lot sweeping and maintenance of storm drainage facilities could be included as part of operating agreements for shopping centers and similar facilities. Operating agreements may be especially important for establishments engaged in the handling of materials which constitute potential pollutants. Examples are gasoline service stations, petroleum wholesalers, trash collection services, and numerous types of manufacturing plants.

6. Subdivision Review

Runoff and drainage controls for new development are most often implemented through amendments to subdivision ordinances. Subdivision regulations dealing with these and other water quality objectives can be expressed either in terms of specific control measures or as environmental performance standards. Performance standards are favorable in that they allow the developer some degree of choice in the design of control measures. However, the success of this approach tends to be highly dependent upon the technical expertise of the reviewing agency. Subdivision review may also be an appropriate point at which to require submission of environmental impact statements by developers. An important issue regarding subdivision review is that, if major reliance is to be placed on this mechanism for water quality control, the regulations should be sufficiently broad to deal with the major development projects which occur. Enabling legislation may therefore be needed in order to cover various classes of single-ownership developments as well as projects involving actual subdivision of land parcels.

7. Zoning

Zoning still represents the primary mechanism of land use control in most communities, to the extent that control exists. The use of zoning as a water quality control instrument typically involves amendment of the zoning code to create special protection districts for critical land areas or water bodies. In view of the fact that zoning has been only moderately successful in guiding land use in most communities, it may be unrealistic to assign a major role to zoning as a water resources protection measure unless: (1) special zoning districts are based on detailed assessments of land-water relationships in the given area, and (2) a strong base of popular support exists for this use of zoning power.

8. Capital Improvements Planning

The location of public facilities such as highways and sewer interceptors is extremely important to the spatial distribution of new development. Thus, public facility planning is potentially a very powerful lever for land use control. This aspect of municipal wastewater facilities should be considered in detail in current water quality planning studies; and the development of waste treatment alternatives should be coordinated with plans for preventing unrecorded pollution, insofar as the latter involve land use control. Heavy reliance upon public facility planning as a means of implementing land use controls tends to involve a large number of legal and administrative issues, however, and should be utilized only as part of a carefully conceived comprehensive planning effort.

9. Acquisition of Land and Conservation Easements

Control of land use through land acquisition or less-than-fee purchase by the public can be an important water resources protection measure, to the extent that the net effect is to shift new development away from areas which are sensitive in terms of either pollutant generation or vulnerability of receiving waters. Similar benefits can be obtained through the action of private groups such as conservation trusts. An alternative approach to land use control, which is ordinarily oriented toward preservation of land in agricultural use, is preferential tax assessment. Such programs have been implemented in a number of states, with somewhat mixed results.

10. PUD/PRD Ordinances

Planned Unit Development and Planned Residential Development ordinances allow much greater flexibility in development design than would be possible under conventional zoning at a given density. Such ordinances can thus be very important to water resources protection by encouraging design modifications which affect runoff and infiltration of rainwater. The most important single aspect of PUD/PRD ordinances is often the reduction in coverage of land by streets and driveways. PUD/ PRD ordinances are most effective for water resources protection when combined with specific runoff control requirements and construction standards; these can either be included as part of the ordinance or implemented through other mechanisms.

A large proportion of these proposed mechanisms for water resources protection are oriented toward land use control. It is important to consider briefly, at a conceptual level, the potential regional water quality benefits that can be attained by implementing land use controls at the local level.

Two general consequences of land use regulation can be identified: (1) change in the spatial allocation of new development within an urban region; and (2) net shift in the types of new development constructed. The first consequence involves the fact that exclusion or restriction of development in one area may simply cause development to go elsewhere within the region. The extent to which spatial reallocation occurs, as opposed to change in development type, depends upon the comprehensiveness of controls within the region and the existence of localized demand factors. For example, suppose that a municipality institutes land use controls which limit construction of conventional single-family housing. If alternative sites are available nearby, and if developers feel that market demand is more significantly related to housing type than to the amenities available in the given municipality, the overall effect could simply be a shift of single-family housing construction to other areas. On the other hand, if constraints upon single-family housing are widespread, developers will be motivated to construct and promote higher-density housing types. (The latter situation is also likely to involve some degree of spatial reallocation, since the relative advantages of different locations within a region tend to be dependent upon the type of development under consideration. For example, high-density housing may tend to gravitate toward existing population centers.)

These rather obvious points are stressed because it is important to avoid the myopic view that exclusion or restriction of new development in a particular area will necessarily benefit water quality in the region as a whole. To the extent that land use control results in spatial reallocation of development, net water quality benefits will result if the land which is protected has at least one of the following characteristics: (1) development of the land would result in higher pollutant yields than equivalent development at other sites; (2) development of the land would constitute encroachment upon surface water bodies, flood plains, or wetlands; (3) the land constitutes an especially important aquifer recharge area; or (4) the land drains to surface waters which are especially sensitive to impact. The first of these characteristics relates primarily to land suitability for on-site sewage disposal and susceptibility to erosion during construction. The important point is that, unless land use control measures specifically direct development away from areas having the above characteristics, there may be little water quality justification for these controls, even though they may be highly desirable for other objectives such as open space preservation, ecosystem protection, efficient energy utilization, transportation planning, protection of agricultural land, and provision of public utilities. If these other objectives are sought, they should be included explicitly as a basis for land use controls.

In many cases, the aspect of land use control which is most important for unrecorded pollution is the resulting shift among development types, particularly the substitution of clustered housing and multi-unit structures for traditional house-and-lot development. The mechanisms which appear most likely to achieve such a shift (with assistance from present market trends) are PUD/PRD ordinances, and capital improvements planning which encourages nodal development in selected districts. However, the water quality benefits thus achieved can in most cases be achieved equally well through the use of mitigative measures.

Choice of Controls

The physical control measures which are felt to be most needed for new urban development have been described in some detail in Section 4. The following areas have been emphasized: (1) control of erosion/sedimentation problems due to construction activity; (2) control of the location, design, and operation of on-site sewage disposal systems; (3) control of hydrographic modification; and (4) construction of leakproof sanitary sewer systems. The present discussion is limited to control measures that are primarily suitable for new development, either because they must be physically incorporated in new facilities, or because they are tactically easier to implement at the time of land use conversion than after a land use has become established.

Table 10 presents a summary of physical controls by type, scope, level of implementation, and nature of problem addressed. The first four controls relate to hydrographic modification (which is the subject of the next section of this report). Runoff detention facilities, which include measures such as storage of rainwater on rooftops and parking lots, are expected to play a major role in water quality control plans. On-site runoff detention devices must ordinarily be included in the original design of a development project. However, detention facilities can be constructed at off-site locations to serve existing development if appropriately located land can be made available for this purpose. In the case of infiltration devices, an important characteristic is that unless soils are extremely permeable, infiltration facilities must ordinarily be dispersed throughout a developed area rather than centralized. The opportunities for use of infiltration devices in existing developed areas thus tend to be very limited.

As discussed in the next section, detention facilities deal with the problem of excessive rates of discharge during storm periods, whereas infiltration devices are most relevant to aspects of hydrographic modification which involve groundwater recharge. Both types of measures reduce the loadings of pollutants released to surface waters. For most types of urban development, the use of properly designed retention and infiltration facilities may provide adequate control of stormwater quality, when combined with sound land management practices. Implementation of these measures can be accomplished at the local level by amendments to subdivision ordinances or by adoption of separate environmental ordinances, the latter of which may deal with a variety of environmental impacts. In some areas of the U.S., voluntary inclusion of runoff controls in major construction projects is becoming common, particularly in cases where a zoning variance is requested.

TABLE 10

CHARACTERISTICS OF POLLUTION CONTROLS

Physical Control	Scope of Control	Level of Implementation	Nature of Problem Addressed
Runoff detention facilities	New and existing development	Local	Peak discharge magnitudes, pollutants
Runoff infiltration facilities	New development	Local	Base flow, aquifer recharge, pollutants
Development design modifications to limit runoff impact	New development	Local	Streamflow regimen, pollutants
Protection of natural watercourses	New development	Local	Aquatic habitats, peak discharge, pollutant transport
Erosion/sedimentation controls for construction sites	New development	State, local	Sediment, runoff quantity
Location and design of on-site sewage disposal systems	New development	State, local	Groundwater quality, pollutants
Construction of leakproof sanitary sewer systems	New development	Local	Infiltration/inflow, pollutants
Private property maintenance and management of hazardous materials	New and existing development	Regional or local	Pollutants
Maintenance of on-site sewage disposal systems	New and existing development	Local	Pollutants
Public cleanliness and facility maintenance	New and existing development	Regional or local	Pollutants

Source: Betz Environmental Engineers, Inc.

Development design modifications, listed in the third row of Table 10, refer to any integral features of development projects which are intended to reduce or retard storm runoff. These may range from simple measures such as limitation of impervious coverage, to carefully-conceived drainage plans which make use of grass swales and buffer strips to promote infiltration. A potentially very beneficial measure is the use of porous pavement rather than conventional pavement, which could involve little or no additional expense in some cases. Protection of natural watercourses from encroachment is important in order to maintain the natural capacity of stream channels to absorb flooding, as well as to preserve aquatic habitats. Ideally, protection measures should extend to small headwater streams as well as major watercourses, and should be linked to flood plain management programs where possible. Policies regarding alteration of watercourses should be included explicitly in subdivision regulations and environmental ordinances.

Erosion/sedimentation controls for construction projects can be implemented directly by state agencies, or more commonly, by counties or municipalities under state enabling legislation. As discussed in Section 11, control of land erosion usually involves the use of mitigative measures rather than restriction of development in areas with high erosion potential. Control of the location and design of on-site septic systems represents largely an extension of existing regulatory functions, which have traditionally been oriented toward health rather than water quality. In regions where large areas of land are intrinsically unsuitable for on-site waste disposal, stringent regulation of new systems may have major implications for land use, since development may not be feasible in such areas without municipal sewerage or use of package treatment plants. The impacts of on-site sewage disposal regulations should therefore be considered carefully in population forecasting and wastewater facility planning.

The last three items listed in Table 10 are controls which can be applied similarly to new and existing development, but which should ideally be established prior to land use conversion. The potential importance of operating agreements for commercial and industrial establishments has already been mentioned. In cases where surface pollutant accumulations are expected to be especially serious, such agreements could include stormwater treatment. One approach is to require establishments engaged in the handling of bulk materials to submit a mass balance accounting of all materials which will enter and leave the premises, given various levels of operation. Satisfactory arrangements for handling and disposal of residuals would then be established as a precondition of the granting of approvals needed for construction. An additional requirement which might be imposed in the case of gasoline service stations is that they be obligated to accept and properly dispose of residual petroleum products (e.g., crank-case oil) when submitted by residents in small quantities.

Maintenance of new on-site septic systems will not differ technically from maintenance of existing systems; but greater latitude may exist for enforcement of standards in the case of new systems. All permits issued after a certain date could possibly be made contingent upon observance of an appropriate maintenance schedule (pertaining primarily to sludge removal), to be verified by a licensed sewer scavenger. The permitting system could also provide for testing at long intervals to assure that a system is continuing to function properly. Finally, with regard to public cleanliness measures and facility maintenance, various steps might be taken in the design of new development to facilitate these activities. Two examples are location of sanitary sewers so that they will be readily accessible for repairs, and design of catch basins to facilitate cleaning operations.

There are numerous issues and opportunities involving the use of stormwater controls which are not discussed here. Some examples are: re-use of stormwater; reduction in required storm drainage when porous pavement is utilized; linkage of the erosion/sedimentation controls provided during construction with permanent stormwater control measures; and design of runoff detention basins as multipurpose facilities. Some useful references in this regard are Lager and Smith (1974), and Tourbier and Westmacott (1974), as well as the Abt Associates report. The present discussion also has not attempted to relate preventive control of unrecorded pollution to municipal wastewater planning, although these activities are linked by a number of critical issues, which involve water supply, inter-basin water transfers, land disposal versus stream disposal of effluents, and regional versus localized treatment systems. For example, one disadvantage of regional sewer systems may be the exportation of water from the areas served, which reduces base flow of streams; but this could possibly be offset by utilization of infiltration devices for groundwater recharge, as described in the next section. Planners should be aware of the existence of these issues, particularly when the use of water quantity controls is under consideration.

A final comment is that the list of preventive controls recommended here for new urban development is intended to represent a feasible strategy for widespread application in U.S. metropolitan areas. It is clear that much more can be done in certain counties and municipalities where interest in environmental issues is high and ample resources exist for implementation of controls. However, regional planning agencies must consider what is achievable in all or a large part of the region. The major preventive controls suggested here--control of on-site sewage disposal, construction of tight sanitary sewer systems, control of hydrographic modification, and control of erosion during construction--are felt to be generally feasible, even though they represent a quantum leap relative to existing practices in a large proportion of communities. When combined with maintenance of high cleanliness standards, these measures should, in most instances, provide a reasonable level of protection against water quality deterioration.

SECTION 9

CONTROL OF HYDROGRAPHIC MODIFICATION

Introduction

Hydrographic modification refers to actions which affect the flow regime of surface waters. The term is most commonly used in describing the effects of major in-stream projects such as dams, diversions, channelization, and so on. The major emphasis of the present section, however, is upon the cumulative effects of widespread actions associated with urban development, including changes in land surface characteristics as well as direct manipulation of receiving water bodies. The discussion will relate generally to all effects of urban development on water quantity (defined as the volume and rate of movement of water at each point in the hydrologic system) and will refer to problems such as aquifer recharge which are not typically associated with hydrographic modification.

As discussed earlier, urban development involves construction of impervious surfaces and alterations to the natural drainage network, which increase the volume of surface runoff and accelerate its movement through the surface water system. These impacts tend to be progressive in nature and may require a long time to occur; the effects produced by each individual development project may be imperceptible. Significant differences in impact are associated with different types of development. For example, with regard to increase in peak discharge, the smallest effect per unit of impervious surface is produced by development with no storm sewerage; next is the effect of urban land with street drains but no alteration of natural streams and swales; and the greatest effect is produced by development in which all watercourses have been replaced by artificial conduits. Similar variation exists in the effects of urban development on low flow magnitudes, although these effects tend to be somewhat more difficult to predict.

It is extremely important to recognize the linkages which exist between hydrologic effects and water quality. In the case of effects on base flow, the linkages involve the quantity of water available for dilution of wastewater effluents and support of aquatic life (as well as for water supply). In the case of surface runoff during storm events, the linkages involve the production of pollutants *per se*. The same factors which increase runoff volume and rates of discharge are critical to production and transport of stormwater pollutants; and measures which control the former effects also exert a substantial degree of control over pollutant loadings. As noted earlier, the latter fact is central to the control strategy suggested here for new urban development.

The next three sub-sections discuss the hydrologic impacts of urban development, and a number of related issues which are important for water resources protection. The remainder of this section deals specifically with the use of runoff detention and infiltration devices as controls for water quantity and quality.

Effects of Urban Development on Peak Discharge and Stream Channel Conditions

Two quantity-related effects of urbanization on storm runoff should be distinguished, namely the increase in total volume of direct runoff, and increase in the peak rates of discharge produced. The latter effect is typically much greater than the former in percentage terms. (See for example Anderson, 1968; and Putnam, 1972.) Urban development in a small basin may increase the total direct runoff resulting from a given rainfall by 50%, but increase peak discharge at the basin mouth by 150% or 200%. This discrepancy, which is due to the fact that runoff is accelerated as well as increased in volume, is attributable both to drainage alterations such as storm sewerage and to the presence of impervious surfaces *per se*.

The effects of urban development on peak discharge can be summarized in either of two ways: (1) the discharge associated with any given frequency (e.g., once in 5 years) is increased; or alternatively, (2) any given discharge level is achieved more often. These effects tend to be most important for small watersheds, due in part to the fact that urban development usually accounts for a minor proportion of land area in large basins (e.g., watersheds of several hundred square miles or more). The impact of urbanization on peak discharge also tends to be relatively greater for moderate storm events, which occur frequently, than for extreme events. The 2-year flood discharge may be increased by only 50%.

A major focus of attention here is the impact of changes in peak discharge on stream channel conditions. The following characteristics of stream channels are relevant to this phenomenon, as well as to a number of other water quality issues.

Under static land use and land cover conditions, stream channels tend to maintain a dynamic equilibrium (or "quasi-equilibrium") condition with stream flow. A high level of interaction tends to exist between the stream channel and the stream water, in the form of erosion and deposition of particulate matter. As described by the classic meander model, a stream is likely to erode the outer bank of its channel in a bend, and to deposit material on the inner bank. Thus, the channel may shift laterally over time. The channel is likely to remain fairly constant, however, in terms of configuration, capacity, and elevation, even while its location is shifting; and the amounts of material deposited and eroded are likely to balance roughly in the long run. Even if the latter is not true, so that the amounts of earth material entering and leaving a stream reach are consistently different, the magnitude of the imbalance tends to be small relative to the gross interchange of material between the stream channel and the stream water.

It has been observed (Leopold, Wolman, and Miller, 1964) that stream channel equilibrium under natural conditions tends to involve a situation in which channel capacity remains roughly equal to the 1.5-year flood discharge. That is, despite lateral movement of the channel, channel size remains just sufficient to accommodate all flows up to the discharge which is equaled or exceeded in two out of three years on the average. Subsequent studies have suggested that, when the streamflow regimen is changed due to urban development, a process of channel enlargement ensues, involving imbalance of erosion and deposition (Leopold, 1968; Hammer, 1973a). The end result appears to be a new equilibrium in which channel capacity is again roughly equal to the 1.5-year discharge. The percentage increase in channel cross-section area due to urbanization is thus comparable to the corresponding increase in the 1.5-year flood. Logically, channel enlargement would not necessarily require a net removal of earth material equal to the change in channel size. The size of a channel can be increased by deposition of sediment on bank tops as well as by scouring. However, surveys of channel behavior over time have suggested that channel enlargement in a stream reach tends to involve a net erosion effect which is very roughly equal to the increase in channel volume (Hammer, 1973a; pages 124-126).

Stream channel enlargement can therefore be an extremely important source of suspended solids and bedload material in urbanizing areas. This effect is a direct consequence of change in streamflow regimen, and is independent of sediment yields from construction sites, and of effects produced by human alteration of stream channels (except that the latter tend to increase peak discharge and channel enlargement downstream). The channel enlargement process not only yields sediment to downstream areas, but also involves channel disturbance over an extended period of time, which can have severe biologic and aesthetic impacts.

The above description, in which channel enlargement is said to involve a temporary imbalance between erosion and deposition processes, should be modified somewhat in the case of rills, gullies, small headwater streams, and perhaps major streams in mountainous and arid areas. The meander model may have little relevance in these cases, since the streams are persistently downcutting rather than interacting with flood plains through selective erosion and deposition. Change in streamflow regimen due to urbanization simply accelerates the downcutting process. There may be no natural limit to the net amount of material thus removed, unlike the case when a stream is prone to lateral movement within a flood plain.

Empirical studies of stream channel enlargement indicate that the ultimate increase in channel cross-section area due to urbanization ranges from 25%-50% for streams draining low density residential development, to upwards of 200% in small basins which are 50% impervious (Hammer, 1973a). The relationships governing channel enlargement are essentially the same as those governing increase in peak discharge, and can be summarized as follows:

1. The hydrologic impact of a given intensity of urban development is less in large watersheds than in small watersheds. Channel enlargement is a

problem primarily in stream reaches draining less than 100 square miles, and tends to be most dramatic in basins of 10 square miles or less.

2. Major differences in impact exist between hydraulically-connected and non-hydraulically-connected impervious surfaces. The effects of the latter are highly dependent upon several factors which determine the probability that runoff will reach the receiving stream, namely, the size of the impervious parcel, the slope of the land on which it is located, and the density of streets in the vicinity.

3. The greatest land use impacts on flood discharge and channel condition are produced by streets with storm sewers, due to the role of street gutters in collecting runoff from adjacent land as well as from street surfaces. The effects of streets vary somewhat according to the efficiency of storm sewerage, as measured by variables such as the density of inlets.

Equations estimated in Pennsylvania studies indicate that the yield of sediment from an urbanizing basin, due strictly to enlargement of stream channels draining more than 100 acres, could be substantially greater on an annual basis than the total sediment yield from the basin while in agricultural use (Hammer, 1973a, p. 140). For a given development project, there are various circumstances under which the total sediment yield due to channel enlargement could be comparable to the yield due to erosion during construction, with or without control measures applying to the latter. Thus, increases in runoff quantity and peak discharge due to urban development are *per se* an important factor in stormwater pollution.

Prevention of Direct Alternation of Stream Channels and other Water Bodies

Water resources protection measures should address at least four objectives regarding stream and river channels, as follows:

1. Prevention of disruption of aquatic habitats

2. Prevention of sediment yield due to channel enlargement

3. Preservation of the natural capacity of stream channels to dissipate flood discharges

4. Preservation of the role of stream channels as a sink for stormwater pollutants.

The discussion in the previous sub-section is relevant to the last of these objectives. Given the interchange of particulate material between stream channels and the stream water which typically exists, and given the extent to which urban stormwater pollutants are associated with suspended material, stream channels would be expected to play an important role as a sink for pollutants. As suggested earlier, this role may be very important in reducing the pollutant loads which reach major water bodies. Loss of pollutants from the stream water does not necessarily require that sediment loads *per se* diminish downstream; the deposition of particulate matter which is high in chemical pollutants could be balanced by erosion of relatively clean material from the channel. Preservation of this role of natural stream channels by preventing alterations such as channelization and replacement by storm sewers is considered generally desirable, especially for headwater streams, although it is clearly not an adequate substitute for eliminating stormwater pollutants altogether.

The capacity of stream channels to dissipate flooding has not been discussed here but is generally well known. Periodic flooding is a natural function of stream channels. Channel alterations and encroachments which prevent this occurrence have the effect of increasing peak discharges and flood-related problems downstream.

Prevention of stream channel enlargement, and associated channel disruption, will be accomplished largely through the use of runoff controls for new urban development, which are the focus of the latter portion of this section. With regard to direct alteration of streams and other water bodies, planning agencies are urged to recommend a general policy of non-intervention. New development should be designed so that streams are left in their natural state, rather than being straightened, channelized, or replaced by artificial conduits. Attempts to improve the appearance of streams by cosmetic measures, such as elimination of trash and grooming of vegetation, should be encouraged; but such measures should stop at the bank top, and should not interfere with natural erosion, deposition, and overflow processes. The serious negative effects of channel alterations on aquatic habitats have been mentioned in Section 5. Due to these effects, and the other factors mentioned here, it is felt that non-interference with stream channels can be recommended as a water quality protection measure.

Clearly, alteration of watercourses is sometimes necessary in order to prevent property damage and safety hazards due to flooding of existing developed land. However, it should be possible to avoid such situations in the future by preventing construction of buildings and other facilities at points where they could be vulnerable to flood damage (taking into account possible increases in flood levels due to future urbanization). Efforts in this regard can be linked to ongoing flood plain planning activities where they exist.

A significant issue is the definition of watercourses to be protected, specifically the choice of an upstream limit of protection. Typically, surface water drainage involves a network of gullies, swales, ephemeral streams, and perennial streams, within which there is no clear point at which controls become appropriate. Channels draining small areas of land can be a liability when affected by urbanization, due to their erosion potential. On the other hand, many small channels may be useful, when retained in natural condition, for dissipation of flooding and entrapment of pollutants. A suggested criterion is that non-intervention policies should extend to all stream channels, no matter how small, for which there exists a flood plain at least as wide as the channel. (An unambiguous definition of flood plains could be developed; see Hammer, 1973a, p. 112.) Alteration or replacement by storm sewers would be permitted for other watercourses draining into these channel reaches; this might even be encouraged in cases where urban development does not include runoff control. Protection of very small stream channels is not without precedent. An ordinance applying to the Wissahickon Creek Watershed in Philadelphia, for example, contains minimum building setback requirements for swales draining as little as 20 acres (Coughlin and Hammer, 1973).

Another potential aspect of hydrographic modification is the creation of impoundments. Impoundments often have beneficial effects on downstream water quality; but the impoundment itself is likely to be highly sensitive to water quality impacts, particularly impacts due to urban runoff. If water quality in the impoundment is to be maintained, more stringent controls on urban runoff quality are likely to be necessary than would be the case without the impoundment. Thus, it is felt here that impoundments generally should not be created in developing or developed areas, except under three conditions:

1. Land development is essentially complete (or land use is expected to remain stable for other reasons) and the water quality of influent streams is demonstrated to be suitable.
2. The unique value of the impoundment to the public (e.g., for municipal water supply) clearly justifies the additional public and private costs of maintaining water quality through land use controls and other measures.
3. The purpose of the impoundment is specifically to mitigate the impacts of urban development on downstream receiving waters.

This is a complex issue, however, and must be resolved largely on a case-by-case basis.

Effect of Urban Development on Groundwater Replenishment

Discussion thus far has focused upon the effects of urban development which involve surface runoff, rather than the consequences of decreased infiltration *per se*. In the absence of urban development, infiltration typically is equal to a large proportion of annual rainfall. (Water which infiltrates only into the top layer of the soil, and then re-emerges as storm runoff, is ignored throughout the present discussion.) Part of the infiltrated water is extracted by vegetation; part percolates downward into deep groundwater reservoirs; and part travels through the soil to emerge eventually in surface water bodies. The last of these components is the major source of streamflow during nonstorm periods. Urban development tends to reduce infiltration, due to construction of impervious surfaces and temporary disturbance of the remaining pervious soil. The expected effect is a reduction in all of the subsurface water components just mentioned. Less water would therefore be available for human use in groundwater aquifers; and streamflow during dry weather would tend to be reduced. As mentioned earlier, reduction in the base flow of streams could be relevant for water supply, maintenance of aquatic life, and dilution of wastewater effluents. This quantity-related effect is therefore considered to be an important water quality issue.

The effects of urban development on groundwater and base flow are somewhat difficult to predict, due to a number of complicating factors. The issues involved can be illustrated by way of a simple example. Consider a small land area which is being converted to medium-density urban use. Assume that water for domestic and other uses will be imported to the area by a municipal authority, and that sewage will be exported via a separate sewer system. Due to construction of impervious surfaces, surface runoff during storms will increase relative to present conditions; and the volume of water infiltrating into the soil will decrease. If the area is to be 30% impervious, one might expect reductions of approximately 30% in the volume of infiltration, the rate of aquifer recharge, and the contribution of the area to base flow in local streams.

However, these factors will all change by considerably less than 30%, for a number of reasons. First, the land development process will involve removal of most or all of the existing vegetation. The 70% of the land kept in soil cover will eventually be replanted with grass, shrubbery, and small trees. The net effect may be a large reduction in evapotranspiration. Second, some of the impervious surface may not be hydraulically connected to storm sewers, particularly if the area is to contain single-family housing. Much of the storm water draining onto pervious soil from these surfaces may infiltrate. Third, the new, carefully-tended vegetation (e.g., grass) may maintain greater soil porosity at the surface than existing vegetation, thus increasing infiltration. And fourth, significant amounts of imported water may be released from the municipal system--i.e., may not be re-exported as sewage. Watering of lawns, and leakage from water and sewer pipes, would be the two primary mechanisms. A very large proportion of this water may infiltrate, if not originally released into the soil.

These factors tend to be particularly important for residential land. In some cases they may cause urban development to affect the net recharge of groundwater by only a small amount, or not at all. Limited evidence in the Philadelphia area has suggested that base flow of streams is just as well-sustained in medium-density urban watersheds, with imported water and no continuous wastewater effluents, as in comparable rural watersheds. Extreme low flows may in fact be somewhat higher. The only exception observed in the Philadelphia case was an industrial basin containing an airport (Hammer, 1973a, p. 229). It appears likely that imported water is the factor most responsible for these findings.

The situation becomes more complex when groundwater withdrawals and sewage disposal are included. On-site sewage disposal constitutes a direct addition to infiltration. Pumpage of water from wells represents a subtraction from the supply of water available in a given aquifer; but the relevant recharge area may be located some distance away from the wellhead. A fairly common case in urban areas is one in which water is imported for domestic use, but sewage is disposed on-site. It is quite clear that this form of urban development involves no net reduction in groundwater recharge, although groundwater pollution may be an issue.

Consideration of water supply and waste disposal opens a number of issues regarding inter-areal water transfers and the value of self-sufficiency in water resources. Without assuming that self-sufficiency will be adopted as a goal, it is recommended here that land development projects not receive credit for the effects of imported water, when impacts on groundwater are computed. This would apply whether or not on-site sewage disposal is involved. Given this position, it would follow that measures to promote infiltration are generally needed for new urban development.

Control of Runoff and Infiltration

The effects of new urban development on runoff and infiltration can potentially be controlled in four ways:

1. Construction of stormwater detention devices
2. Construction of infiltration devices
3. Modification of development design
4. Control of development location

Stormwater detention devices and infiltration devices are offsetting measures which do not necessarily require alteration in the design of other functional elements of a development plan. Such measures can be integrated with other facilities if desired, as is the case when rooftops and parking areas are used for stormwater storage. Modification of development design, as a hydrologic control, includes all measures to reduce runoff and promote infiltration which do not involve construction of specific physical facilities for this purpose. Control of development location involves change in overall land use patterns, relative to what would otherwise occur, in order to minimize hydrologic impact.

Detention devices are considered here as a generic class of facilities which operate automatically to store stormwater for the purpose of slowing its rate of movement through the surface water system. Water storage capacity is obviously a necessary feature of detention devices, since reduction in the rate of surface water movement can only be achieved by creating a situation in which the rate of inflow to an area is greater than the rate of outflow, during some critical period. The simplest type of detention facility, which also tends to be most cost-effective for development projects involving large tracts of land, is the detention basin. This is simply a surface impoundment in which the outlet is designed and operated so that excess storage capacity exists prior to a storm. Stormwater from areas served by the basin is conducted to the basin by pipes or natural channels, and then released at a controlled rate which is less than the peak rate of inflow.

As applied to new development, a detention basin can be visualized simply as a water storage area with a big pipe coming in and a small pipe going out. A variant of this is a paved area or rooftop upon which ponding occurs, so that the rate of runoff from the surface is less than the rate of precipitation. If a detention basin is not lined with impermeable material, and is located on highly pervious soil, a significant amount of infiltration may be achieved during periods of storage, so that the total volume of water released through the outlet is substantially less than the volume of inflow. This does not hold for a majority of detention facilities, however. Detention structures and infiltration devices will thus be kept conceptually distinct here for purposes of simplicity.

Infiltration devices are facilities designed specifically to promote infiltration of stormwater into the soil. Infiltration devices can be located either above or below ground, although below ground facilities tend to be more common. Examples are French drains, seepage pits, and Dutch drains. A critical feature of infiltration devices is that they are almost always designed to induce infiltration into a soil surface which is much smaller than the catchment area served by the facility. Thus, the rate of infiltration is generally less than the peak rate of inflow, which means that storage capacity must be provided. For example, an infiltration device serving a rooftop area could not consist simply of an extension of the gutter downspout into the soil. A subsurface area filled with porous material such as gravel or stone would be required, in order to provide space for temporary storage of water while infiltration is taking place. The present discussion will assume that a surface or subsurface storage area is always needed, and is likely to constitute the major cost factor involved in constructing an infiltration facility. Although an infiltration device may include an outlet, as in the case of a Dutch drain, it will be assumed here that there is no release of water from storage other than through infiltration. When storage capacity is fully utilized during a storm event, additional stormwater simply bypasses the facility.

Detention devices and infiltration devices differ in that the former affect only the timing of runoff release during a storm period, not the volume, whereas the stormwater which enters infiltration devices tends to make little or no contribution to stream discharge during the high-flow period associated with a given storm. Despite this advantage of infiltration facilities, detention devices tend to be more feasible for control of peak discharge, due to the generally lower cost of providing large amounts of storage capacity, and the fact that the operation of detention devices is independent of soil characteristics.

Development design modifications for the purpose of minimizing runoff and promoting infiltration fall primarily into three categories: (1) limitation of impervious coverage; (2) use of porous paving materials; and (3) drainage plans which expose runoff from impervious surfaces to pervious soil. Limitation of impervious coverage is a potentially favorable approach which can often be accomplished without reducing land use intensity. For example, clustered housing, as accomplished through PUD ordinances and other mechanisms, tends to involve less street area and other impervious surface per dwelling unit than conventional single-family housing. Impervious coverage can be reduced by selectively eliminating paved areas, or substituting other forms of surface, in cases where pavement is not highly needed. Examples are paved sidewalks in low-density residential areas, and overflow parking lots for shopping centers. Often this can be accomplshed simply by amending the requirements specified in existing municipal ordinances.

Porous paving material, which contains interstices that allow stormwater to pass through to the underlying soil, has not yet been widely tested, but is regarded as extremely promising (Tourbier and Westmacott, 1974). The ability of porous pavement to withstand heavy traffic and to remain unclogged over long periods of time has not been proven; but this material should be suitable for walks, drives, and parking areas that are not intensively utilized. As is true also in the case of infiltration devices, the value of porous pavement for water quality control may be limited by the fact that the surfaces containing the greatest pollutant accumulations are likely to be those which are least suitable for use of this measure.

It is possible to induce infiltration and to moderate the volume and speed of surface runoff by providing drainage plans which allow runoff from impervious surfaces to cross pervious soil. Runoff from rooftops can be directed onto lawns, for example, rather than channeled to streets or storm sewers. The use of grass swales rather than impervious drainage conduits can also be beneficial in some circumstances. For very low-density development, it may be possible to minimize the use of storm sewerage even for street surfaces. Residential developments in southeastern Pennsylvania, for example, which are less than 20% impervious overall and are located on moderately permeable soils, typically show no ill effects from lack of elevated street curbs and storm sewers; good grass cover is maintained to the margin of the roadway. The potential importance of this is indicated by the finding mentioned earlier that the hydrologic impact of urban development, per unit area of impervious surface, is very strongly related to the extent to which impervious surfaces are hydraulically connected. On the other hand, the danger of providing only minimal drainage facilities, and/or utilizing pervious drainage channels, is that erosion or ponding will occur, plus possible safety hazards in the case of street surfaces. Thus, land slope and soil conditions must be considered carefully.

Control of the location of new development, as a means of minimizing runoff and infiltration effects, could involve two aspects of location: proximity of development sites to watercourses (or to specific stream segments considered important for protection); and on-site characteristics of the land, such as soils, slope, and existing vegetation. Emphasis upon the first aspect might lead to plans in which stream valleys were designated as corridors of protection, whereas emphasis upon the latter might lead to protection of dispersed "sensitive areas." Empirical evidence suggests, however, that the hydrologic impact of completed urban development is much less sensitive to location factors than to development design (Hammer, 1973a). This finding applies to conventional types of development, in which a large proportion of impervious surfaces are hydraulically-connected. An implication is that control of development location is beneficial primarily when combined with design modifications, and/or the use of runoff control devices. This conclusion is believed to be generally valid also with regard to the impacts of development on water quality caused by washing of pollutants from impervious surfaces.

In the approach recommended here, the use of runoff detention and infiltration devices is generally favored over reliance upon development design modifications or land use controls. The design modifications mentioned are worthy of encouragement, but have the following disadvantages for use as primary water resources protection measures. First, these are essentially partial measures; thus, preventive devices such as detention basins must also be utilized if full protection against hydrologic impacts is to be achieved. Second, the effectiveness of design modifications (other than limitation of impervious surface) are difficult to establish quantitatively. This is a very important issue since many municipalities do not possess adequate technical resources for detailed review of runoff control plans submitted by developers. In contrast, the appropriate design parameters for detention and infiltration devices can be established in a fairly unambiguous manner; and guidelines regarding these parameters can be developed by planning agencies at the regional level (see below). Third, development design modifications tend to be most feasible in cases where they are least needed in terms of water quality. With regard to control of development location, such controls are difficult to implement unless imbedded within an overall environmental plan, which deals with land use issues at a much more detailed level than is possible in current regional water planning efforts.

The strategy recommended here would involve stringent control of the hydrologic impacts of new development, as a means of achieving both water quantity and water quality objectives. Primary emphasis would be placed on use of detention and infiltration devices (although performance standards allowing partial substitution of other controls might be appropriate in communities possessing strong capability for technical review). The desired situation would involve "zero impact" regulations, wherein new development projects--public or private--would not be allowed to increase peak discharge at any point in the surface water system, and would not be allowed to decrease the net rate at which groundwater is replenished. Further details regarding these objectives are discussed below.

It is clear that achievement of these objectives through stormwater detention and infiltration would produce significant water quality benefits, over and above the benefits involving stream channel conditions. Detention devices are moderately effective in reducing stormwater pollutant loadings, due to the tendency of suspended materials to settle out while stormwater is in storage. The degree of pollutant removal is highly dependent upon the storage capacity provided and the time of detention. A detention basin which is adequate for peak discharge control will reduce pollutant loadings in stormwater by roughly the following amounts: 40% to 80% for suspended and settleable material; very little reduction for dissolved material; and 25% to 50% for constituents such as organics which are transported partly in dissolved form and partly in association with particulate matter. Greater pollutant reductions are potentially achievable through the use of infiltration devices, since runoff entering the device is prevented from contributing to pollutant loadings during the given storm (although subsequent groundwater pollution could be a problem, as mentioned below).

Given the review of empirical data which has been discussed earlier, it is felt that the degree of water quality control which will be achieved by strict regulation of runoff quantity can probably be considered a reasonable goal, in current water planning efforts, for most types of new urban development. This assumes that other controls dealing with construction sites and on-site waste disposal will be implemented; that tight sanitary sewer systems will be constructed; that detention and infiltration devices will be maintained adequately; and that ongoing programs will be conducted to maintain high cleanliness standards and proper management of potential pollutants. Also, it is recognized that additional control devices could be needed for specific land uses with high pollutant-generation potential (e.g., certain manufacturing operations and other establishments engaged in the handling of bulk materials).

This strategy of focusing upon water quantity effects as a basis for water resources protection is geared to the relatively low level of knowledge which presently exists regarding the effects of stormwater pollution in urban areas. Until more is known about the seriousness of transient phenomena, and about the ultimate impacts produced by conservative materials contained in stormwater, it will be difficult to establish the appropriate levels of control with any certainty. The measures proposed here have the advantage that they would involve construction of runoff storage capacity in conjunction with new development. If later determinations are made that greater pollutant removal is needed, this storage capacity (primarily in detention basins) could be utilized in chemical treatment programs. Emphasis upon runoff storage capacity thus has an important aspect of flexibility in allowing for future upgrading of control practices.

The costs of runoff quantity control are generally moderate. Since detention and infiltration devices operate automatically and do not require a high level of maintenance, the major expense is the initial investment in physical facilities. Thus, most of the cost of runoff control can be assigned to the builder (although the public may assume responsibility for maintenance of facilities). As an example, the direct expense involved in providing runoff detention facilities adequate to deal with the 10-year flood is estimated by Betz Environmental Engineers (1975) to range from 0.1% of total development cost, up to an absolute maximum of 5% of development cost. Although detention and infiltration devices may create opportunity costs, by constraining somewhat the utilization of land in development sites, these measures are felt to be generally feasible for virtually all types of new urban development.

The use of water quantity rather than water quality as an explicit basis for design of controls has a number of tactical advantages. Quantity-related problems such as flooding and erosion are well-known to the layman, and are already a subject of concern in many communities. The performance of control facilities in terms of water quantity is relatively easy to monitor. The goal of "zero impact" (which could not be feasibly employed in dealing directly with stormwater quality) provides an unambiguous benchmark for design of controls. Such a benchmark is often very important in allaying criticism that regulations are arbitrary. The ability of detention and infiltration devices to achieve these standards is a function of relatively few design parameters in each case. The appropriate values of these parameters may be difficult to determine with certainty; but their logical basis is intuitively understandable. Finally, considerable experience already exists in the use of detention and infiltration devices. The feasibility of regulations requiring these measures has been demonstrated, as well as the effectiveness of the measures themselves. (See for example: ABT Associates, 1976.)

It is recommended that regional water planning agencies attempt to provide as much technical guidance as possible, within the scope of current studies, for implementation of water quantity controls. Since the appropriate design parameters for detention basins and infiltration devices are related to relatively few variables, it might be feasible to develop suggested values of these parameters for the whole study region. (The values might be presented in tabular form; and the subareas to which specific tables apply would be mapped.) A particular concern here is that sufficient runoff storage capacity be provided, in both detention devices and infiltration devices. It is felt that regional planning agencies may be in a somewhat better position than local governments to determine the capacities needed to meet zero impact standards.

The various types of runoff control devices available, and the manner in which they should be constructed, have been discussed elsewhere in the literature; an excellent source is the compendium of controls prepared as part of the Christina Basin Study in Delaware (Tourbier and Westmacott, 1974). The remainder of the present section will deal with conceptual issues involving design of detention and infiltration facilities to meet specific performance standards.

Design of Detention Devices

As indicated previously, the essential features of a detention device are a water storage area, an outlet structure, and one or more inlet structures. The outlet is assumed to operate automatically whenever there is water in the storage area. Generally, the rate of release is positively related to the surface elevation of the stored water. An overflow structure (e.g., a spillway) is also provided in most cases. This operates only when the storage area is full, and the rate of inflow continues to exceed the capacity of the outlet.

A detention device can only reduce discharge significantly while excess capacity exists in the storage area. When the storage area is full, and overflow is occurring, the total rate of outflow approximately equals the rate of inflow, so that the structure has little effect. The critical factors in the design of a detention device are thus the volume of storage provided, and the flow capacity of the outlet.* These are the factors which determine the probability that excess storage capacity will exist at any given time. A detention device is said to provide adequate control of discharge during a storm event if (1) the rate of release through the outlet is not unacceptably high, and (2) overflow does not occur during the storm. Design of a detention device usually involves selecting an outlet capacity and a storage volume which will allow these conditions to hold during a single "design storm," defined in terms of a given intensity and duration of rainfall.

The "zero impact" standard for detention facilities is that peak discharge should not be increased relative to conditions which prevailed before development. Estimates of discharge prior to development are thus neccessary for design of these facilities. Although many estimating techniques for small catchments are available, it is recommended here that hydrologic analysis be linked to materials prepared by the U.S. Department of Agriculture, Soil Conservation Service. The specific reference utilized here is the excellent S.C.S. manual entitled "Urban Hydrology for Small Watersheds" (S.C.S., 1973). This document contains simplified methods for routing streamflow, as well as methods for selecting detention basin design parameters. The present discussion will consider some of the issues which arise when such a methodology is employed.

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* Since the rate of flow through the outlet at any time depends upon the amount of water in storage, it is conventional to define outlet capacity as the maximum release rate which occurs when the storage area is full but not overflowing.

A major decision in runoff planning is the choice of a design storm, which expresses the level of protection that a detention facility is intended to provide. Use of a 10-year storm, for example, represents a decision that there should be no increase in the peak discharge produced by a storm which is equaled or exceeded only once in every 10 years on the average. It is commonly assumed that a detention facility which controls a given design storm will also prevent increase in discharge during all smaller storms (although this is not necessarily true, as shown below). Detention facilities which are constructed for flood control purposes usually are based on very low-frequency storms, such as a 50-year or 100-year storm.

When detention facilities are recommended as part of current water planning studies the explicit justification for these controls may be limited to prevention of stream channel enlargement, channel disruption, and the resulting sediment yield. These factors can only justify detention facilities which deal with relatively frequent storm events, since channel characteristics relate primarily to high-frequency floods. As noted earlier, the channel-forming discharge tends to be the 1.5-year flood.* However, the objective of preventing channel-related effects can justify control of somewhat rarer events than this. The general situation is depicted in Figure 8. Relationships between discharge and recurrence interval, based on a hypothetical small catchment in Pennsylvania before and after urbanization, are shown by solid lines. Without preventive measures, the effect of urban development is to increase the discharge associated with each recurrence interval. (The percentage increase is inversely related to recurrence interval.) The upper dashed line indicates the discharge relationship that might prevail if detention facilities were utilized, which were capable of controlling a 1.5-year storm event. As suggested earlier, detention facilities have relatively little effect on discharge during events which exceed the design storm, i.e., which cause overflow to occur. Thus, the discharge relationship under discussion rapidly approaches the relationship denoting no preventive measures, when recurrence intervals greater than 1.5 years are considered. It is reasonable to assume that stream channel enlargement and disruption would occur in such a situation, even though the 1.5-year flood *per se* is controlled. The lower dashed line denotes a situation in which detention facilities have been designed to deal with the 5-year flood. Here, control should be achieved for all of the recurrence intervals relevant to channel characteristics. This is felt to be a more realistic design, in cases where channel protection is the major objective.

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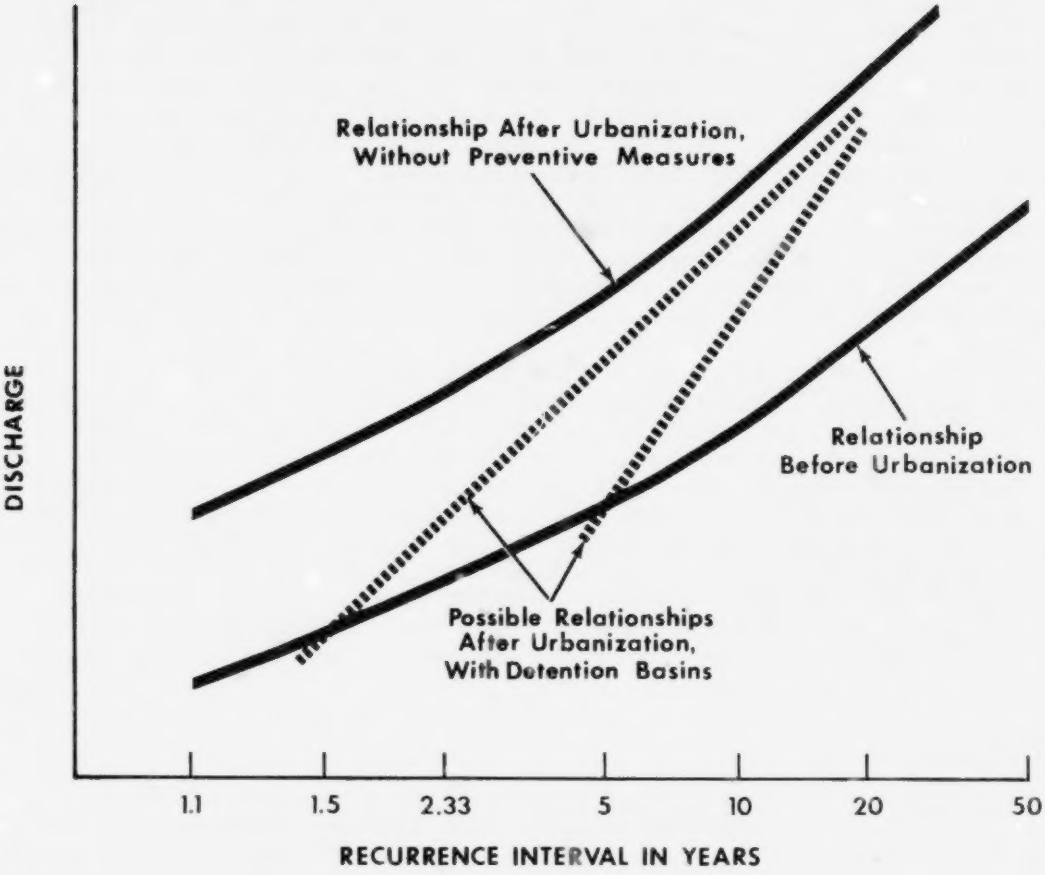
* This means that (1) channel characteristics tend to be correlated more highly with the 1.5-year flood discharge (estimated using an annual series) than with the discharges associated with other recurrence intervals; and (2) channel capacity tends on the average to equal the 1.5-year flood. These characteristics are illustrated in Hammer (1973a).

Control of events greater than the 5-year storm is nevertheless highly desirable, and should be required whenever it is feasible to link water quality objectives with flood control objectives. In addition to providing greater flood protection, the use of an infrequent event as the design storm has important structural implications for detention facilities. These facilities, as applied to new urban development, typically consist of an impoundment formed by an earthfill dam. If the basin is designed to deal with an infrequent event such as the 50-year storm, overflow of the basin will occur with a correspondingly low frequency. Under these circumstances, it is normally adequate to provide an unpaved spillway, consisting of an undisturbed soil surface located at either side of the dam. However, in cases where overflow occurs every 5 or 10 years, it may be



Source: Betz Environmental Engineers, Inc.

Figure 8 HYPOTHETICAL FLOOD-FREQUENCY RELATIONSHIPS

necessary to provide a concrete spillway. This adds substantially to the cost of the dam, and may offset the savings of providing less storage capacity.*

Conventionally, the event selected as the design storm for a detention facility is assumed to involve a spatially uniform pattern of rainfall. The duration of rainfall is subject to discretion. (In applying the "rational method," for example, the rainfall duration is a function of basin characteristics.) The S.C.S. methodology cited here is based on a 24-hour storm, with a "Type II" distribution of rainfall over time. The methodology is applied by consulting rainfall records or generalized maps to determine the 24-hour rainfall magnitude corresponding to the chosen recurrence interval (e.g., the 5-year, 24-hour rainfall in inches). This quantity is used to compute runoff volume, which is then routed through the watershed under study using various simplified techniques. It should be noted that the S.C.S. methodology is inherently conservative when applied in many regions of the U.S., since the Type II rainfall distribution--which is highly concentrated in time--represents a worst-case condition rather than an average condition.

Several issues involving design of detention facilities can be illustrated by considering the hypothetical example shown in Figure 9. An area of roughly 100 acres within a watershed is to be developed; this is depicted in Figure 9 as "zone 3." Since the area consists of a single catchment, the developer has chosen to provide runoff control by constructing a single detention basin at the mouth of the catchment (point A). The detention basin is to involve an earthfill dam with a single outlet pipe through its base. The watershed data which are utilized in evaluating the performance of this basin are shown in Table 11; the reader

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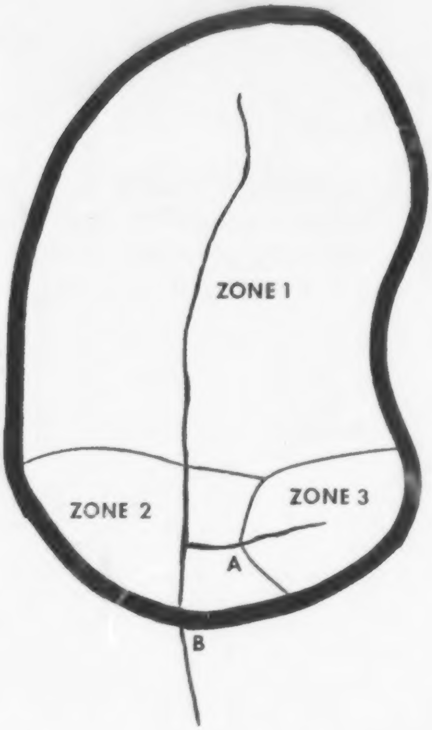
* A recent environmental ordinance in the City of Philadelphia requires runoff controls for new development in the Wissahickon Creek watershed. Preservation of natural stream channels was the primary justification for these controls; and original specifications called for the use of a 5-year design storm (Coughlin and Hammer, 1973). The Water Department subsequently requested use of a 25-year storm, however, in order to limit legal responsibility for possible problems involving overflow.



Source: Betz Environmental Engineers, Inc.

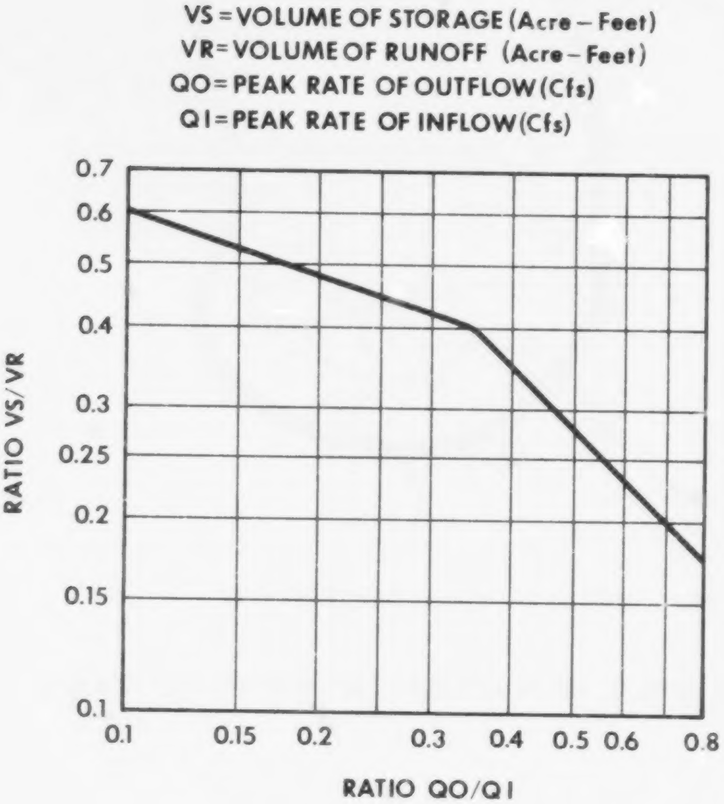
Figure 9 HYPOTHETICAL WATERSHED USED IN HYDROGRAPH COMPUTATIONS

TABLE 11

DESCRIPTIVE DATA FOR HYPOTHETICAL WATERSHED

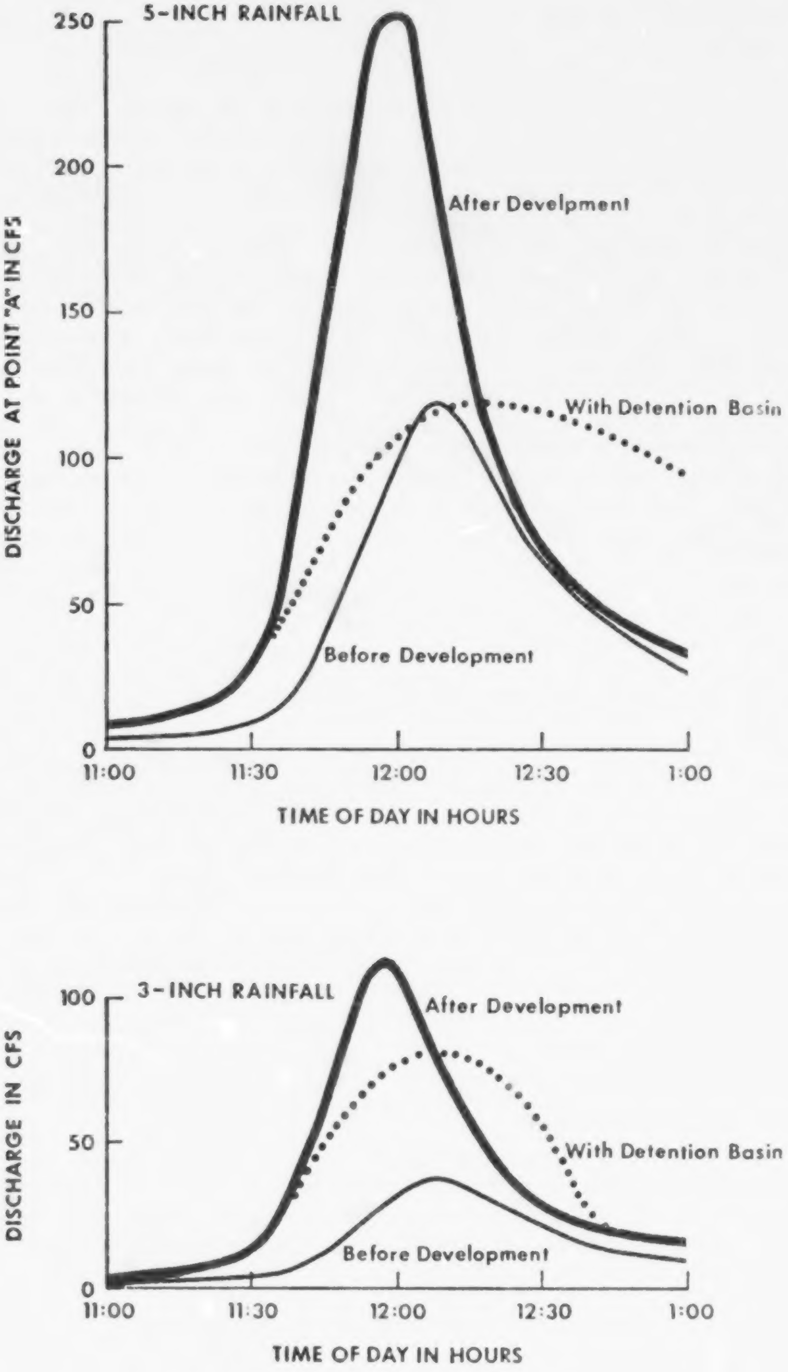
Zone No.	Drainage Area (Mi^2)	Time of Concentration (Hours)	Time of Travel (Hours)	Runoff Curve No.	Storm Runoff (inches) 5" Rainfall	Storm Runoff (inches) 3" Rainfall
1	1.50	1.25	0.25	65	1.65	---
2	0.35	0.75	0.00	65	1.65	---
3-Present	0.15	0.50	0.25	65	1.65	0.51
3-Future	0.15	0.25	0.25	80	2.89	1.65

Source: Betz Environmental Engineers, Inc.



Source: S.C.S., 1973

Figure 10 RELATIONSHIP FOR DETERMINING REQUIRED STORAGE CAPACITY OF DETENTION BASINS



Source: Betz Environmental Engineers, Inc.

Figure 11 DISCHARGE HYDROGRAPHS AT POINT "A"

is referred to the S.C.S. manual for discussion of these variables.

Assume that the county or township in which the hypothetical development is located has an ordinance which specifies that the maximum rate of discharge from a development site during a 10-year storm shall not exceed the corresponding rate of runoff before development. The 10-year, 24-hour rainfall in the given region is a 5-inch rainfall. The S.C.S. methodology indicates that, before development, the peak discharge produced by this storm at point A is 118 cubic feet per second. Following conventional practice, the first step in designing the detention basin is to specify that the flow capacity of the outlet pipe--i.e., the rate of outflow when the basin is full--will be equal to 118 cfs. It is then determined that a storage volume of 5 acre-feet (215,000 cubic feet) will be sufficient. Given this volume of storage, the basin will fill to capacity but not overflow in the 10-year design storm. The S.C.S. handbook presents graphical methods for determining storage volume very quickly. One of these graphs is presented here as Figure 10; the curve shown is utilized to determine "Vs" on the basis of the variables, Vr, Qo, and Qi.

The performance of the basin in a 5-inch storm is shown in the upper portion of Figure 11. The solid lines are hydrographs (plots of discharge versus time) representing discharge from the catchment before and after development, without the detention basin. (The time scale shown in the diagram represents an arbitrary time-of-day assignment used in the S.C.S. handbook.) The dashed line in Figure 11 shows discharge from the catchment when the detention basin is provided. This hydrograph represents flow through the basin outlet.* Since the upper solid line represents inflow to the basin, the rate of inflow exceeds the rate of outflow from about 11:30 o'clock until 12:15. The basin is filling

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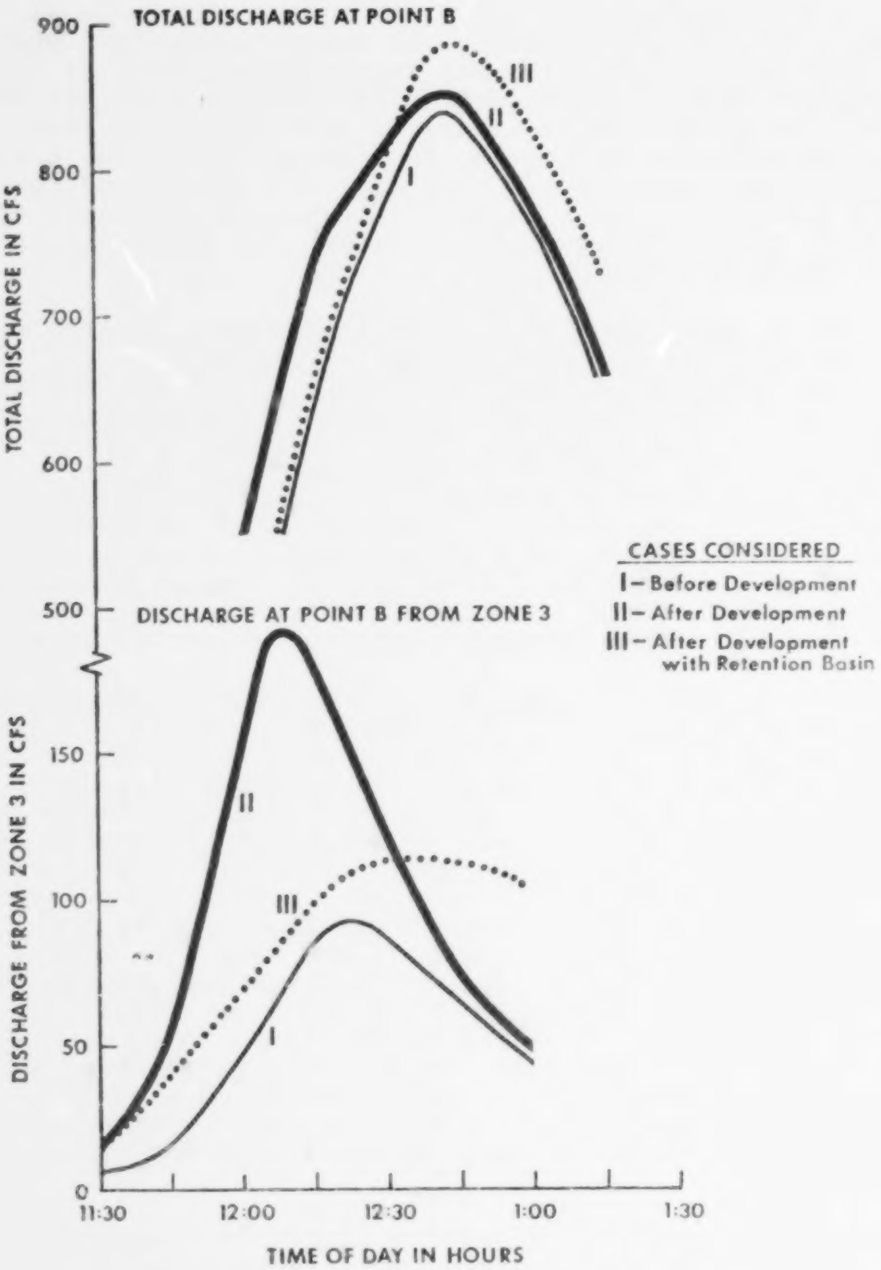
* Unlike the other hydrographs, detention basin outflow in this example was not computed using the simplified S.C.S. methods. It was necessary to assume specific storage/elevation and elevation/discharge relationships in order to illustrate various points discussed below.



Source: Betz Environmental Engineers, Inc.

Figure 12 DISCHARGE HYDROGRAPHS AT POINT "B"

during this time. At 12:15, where the curves cross, the basin is very nearly full, and the rate of flow through the outlet is equal to the peak discharge which would have occurred before development (118 cfs). After this point, the rate of outflow exceeds the rate of inflow, and the volume of water in storage decreases. Thus, the basin effectively spreads out over time the release of runoff from the catchment. This example illustrates two very important points which are generally relevant for the design of detention basins.

First, a detention facility which controls a given design storm will not necessarily prevent increase in the discharges produced by smaller storms. The lower portion of Figure 11 illustrates what happens in the present example during a 3-inch rainfall. Peak discharge increases by 100%, even with the detention basin, since water entering the basin runs directly through within a short period of time. The outlet pipe, which has been sized to deal with a 10-year storm, is too large to provide adequate control in this case. Given that the 3-inch rainfall represents perhaps a 1-year event, it is very likely that this basin would not prevent channel enlargement and disruption downstream.

Second, a detention facility which controls peak discharge at one point may not provide adequate control at other stream points. This fact is illustrated by Figure 12. The hydrographs in Figure 12 pertain to stream discharge at point B, which subtends the entire watershed shown in Figure 9. The lower portion refers just to the discharge at point B which is contributed by zone 3 (the development area). The upper portion of the diagram, which utilizes a different vertical scale, shows the overall discharge at point B. An important fact is that, without the detention basin, runoff from zone 3 tends to arrive at point B well before the overall peak discharge at B, due to the circumstance that zone 3 is located near the mouth of the given watershed. One effect of development in zone 3 without the detention basin is to advance the arrival of runoff at point B. As a result, the overall peak discharge at B is increased very little. (Compare curves I and II in the upper portion of Figure 12.)

The dashed curves in Figure 12 depict the conditions which prevail if the detention basin is constructed as described. An interesting fact revealed by the lower curve is that the peak rate at which discharge is delivered to point B from zone 3 is greater with the detention basin that before development, by about 22 cfs. This occurs even though the basin effectively prevents increase in peak discharge at point A. The reason is that, under most conditions, runoff from a given land area tends to be dispersed during flow in natural channels, due to overbank storage and other factors. As a result, the peak rate of discharge contribution is reduced downstream. In the present example, zone 3 before development yields a peak discharge of 118 cfs at point A, but only 92 cfs at point B. However, this dispersion effect is reduced when detention basins are provided, since detention basin outflow produces a relatively "flat" hydrograph. In the present case, discharge from the detention basin at point A remains near its peak long enough for equilibrium flow conditions to develop in downstream channel reaches, with the result that the peak is effectively transmitted to point B.

A second effect is that, because of the runoff delay accomplished by the detention basin, the arrival of this flow at point B now coincides with the arrival of runoff from the major land area in the watershed (zone 1). The dashed line in the upper portion of Figure 12 shows that the net result of these two effects is an increase in overall peak discharge, relative to both the pre-development condition, and the post-development condition without the detention basin. The magnitudes of these increases are 50 cfs and 38 cfs, respectively. The detention basin thus makes matters worse at point B.

Although this particular example is somewhat artificial, in that it reflects the rigidities of the design storm concept used by S.C.S. and others, it demonstrates a critical issue in detention basin design, which can be summarized briefly as follows. For any given watershed and recurrence interval, peak discharges at points within the watershed tend to vary less than proportionally with drainage area. (On the East Coast, peak discharge typically varies as the 0.8 power of drainage area.) This is due to: the dispersion effect just discussed; variation among subareas in terms of travel time to specific stream points; and the fact that real-life conditions often involve non-uniform rainfall. Detention basins, by creating relatively flat hydrographs for subareas, tend to minimize the importance of the latter factors. The result is that peak discharge tends to be more nearly proportional to drainage area. Situations can then develop in which there is no increase in peak discharge from each subarea of an urbanized watershed, and yet there are serious flooding and channel enlargement problems on the mainstem.

Given these issues, it is obviously desirable to develop design criteria for detention basins which will guarantee uniform protection against peak discharge increase, for all recurrence intervals up to the design recurrence interval, and for all relevant stream points.

The need to provide protection against a variety of storms has special implications for basin design. Specifically, a design in which the stored water drains directly into a single outlet pipe or culvert may not be adequate. It may not be possible to achieve an appropriate rate of outflow when the basin is nearly full, without releasing too much water when the basin is nearly empty. One way to increase the variation in outflow rate is to have water enter the outlet by way of a perforated riser pipe. The perforations would be arranged so that the riser has a constraining effect on the rate of release until a large proportion of storage capacity is utilized. An alternative solution is to provide two or more outlets at different elevations.

Determination of the optimal storage capacity and outflow rates to provide uniform protection against discharge increase is potentially very complex. Evaluation of detention basin performance, assuming a given design, may require direct computations based on the storage-discharge relationship, rather than the use of simplified methods. In determining design parameters, it is theoretically necessary to consider the effects produced at numerous downstream points, in order to determine the point which is most constraining in terms of permissible outflow. (Also, the most constraining point may shift over time, due to various effects of urbanization.) Although such computations can be carried out on a selective basis, to serve as demonstrations or to defend runoff control requirements when challenged, a much simpler procedure is suggested here.

Flood frequency relationships (such as depicted in Figure 8) would be established on the basis of empirical data for a number of watersheds about 5 square miles in size. The flood-frequency relationships would represent pre-urbanization conditions. If peak flow characteristics were known to vary systematically within the study region (due to factors such as soil associations and topography) hydrologic zones could be designated, each of which would be represented by one or more of the sample basins. Such zones might already have been designated in regional flood-frequency studies published by the U.S. Geological Survey. Appropriate outflow rates for detention basins would then be obtained directly by converting these discharge rates to an areal basis. For example, suppose that a 25-acre development site is located in a hydrologic zone for which the 5-year flood discharge in a 5-square-mile watershed is 750 cfs, or 150 cfs per square mile. Assuming that a 5-year design storm is relevant, the maximum outflow rate for the detention basin serving this development would be: (25/640) 150 = 6 cfs. Maximum outflow rates for storms less than the design storm would also be computed in this fashion. For example, if the 1.5-year flood in the abovementioned watershed were 375 cfs, or 75 cfs per square mile, the maximum outflow rate from the detention basin during a 1.5-year rainfall should be about 3 cfs.

The use of a 5-square-mile watershed as the standard for these computations represents a compromise among several factors, and has no theoretical basis; but the outflow rates thus yielded are thought to be appropriate. Regardless of the methodology utilized for this purpose, the important points are the following. First, reasonable rates of outflow for detention facilities (per unit area of land served by the facility) can be established on a regional basis. The storage capacity required to prevent overflow in the design storm can then be determined for a given development site, on the basis of land characteristics and the (tentative) storage-discharge relationship for the detention basin. A regional planning agency could provide tabulated values of storage capacity, for a series of assumed cases in each hydrologic zone, as a type of planning assistance to local communities. Second, whatever the fashion in which outflow rates are derived, they should be very much lower than the rates obtained by considering only discharge from a development site _per se_. The methodology suggested here yields maximum outflow rates which are only between 20% and 50% as great as the rates obtained in the fashion just noted, for development sites ranging from 1 to 100 acres. Third, the use of low maximum outflow rates, and additional constraints on outflow during partially-full conditions, will have major effects on the volume of storage capacity required.

Design of detention facilities with excessive outflow rates is believed to be a major flaw in present runoff control practices, which in some cases practically nullifies the value of detention facilities. Although low outflow rates are fully justifiable on the basis of runoff quantity considerations, their recommendation here is importantly related to the strategy of using detention facilities as water quality controls. Low outflow rates greatly increase stormwater detention time, and thus significantly improve the efficiency of detention devices in reducing stormwater pollutant loads.

Design of Infiltration Devices

In concept, the use of infiltration devices is perhaps the most appealing form of water quantity control, since it parallels most closely the natural processes which are lost when land is covered by impervious surface. The present discussion will be limited to the typical situations in which soil permeability is not so great that infiltration devices can be used feasibly to control peak discharge. Thus, the following objectives of infiltration devices are of primary concern:

1. Aquifer recharge
2. Maintenance of base flow in surface waters
3. Reduction in pollutant yields to surface waters

The design of infiltration as described here will relate only to the first two of these objectives, although a methodology for estimating the reduction in pollutant loadings achieved by these devices is mentioned. The "zero impact" standard that infiltration devices would be designed to meet would be that new development should not result in a decrease in net infiltration--defined as infiltration minus evapotranspiration (minus infiltrated water which re-emerges as surface runoff during storm periods).

Ideally, the design parameters for an infiltration device would be determined through a process such as the following. Factors which affect infiltration such as vegetation, soil type, land gradient, and hillslope position would be established for the development site. On the basis of these variables, and the detailed development specifications, annual infiltration and evapotranspiration would be estimated, for conditions before and after development. Effects involving imported water, on-site sewage disposal, and pumpage from wells would be ignored in the latter case. Infiltration devices would then be designed to compensate for the computed annual reduction in net infiltration, using techniques such as the Hydroscience methodology discussed below. The performance of infiltration devices involves a trade-off between storage capacity and the rate at which infiltration is achieved, which is analogous to the trade-off between storage capacity and outflow rate for detention basins. Since the rate of infiltration within a device involves all of the variables listed above, these would have to be consulted again in determining the appropriate design for a specific facility.

Such a procedure is obviously infeasible in most instances, and is described only to illustrate the factors involved. The actual approach recommended here would involve an extreme level of generality. The first task would be to obtain a regional estimate of net infiltration under rural conditions. A gaged watershed in a rural area would be selected, for which it could be assumed that net groundwater flow into or out of the basin was negligible relative to surface and subsurface flows within the basin. Long-term streamflow records would be analyzed; and base flow separation techniques would be applied to obtain an estimate of annual base flow in inches. Annual infiltration minus evapotranspiration would then be computed as the sum of the following (all in watershed inches per year): base flow, plus exported water, minus imported water. This estimate of infiltration minus evapotranspiration would be considered to hold uniformly for all areas of land before development. The error involved in this assumption should not be overly serious, since underprediction or overprediction of net infiltration in any particular case should be followed by a corresponding underprediction or overprediction of the performance of infiltration devices after development.

In regions of the U.S. where natural vegetation is relatively lush, it may be adequate to assume that infiltration and evapotranspiration per unit area of pervious soil are the same both before and after land development. The effect of development would then be simply to reduce net infiltration by the same proportion that pervious soil is reduced. A different formula could be used when natural vegetation is sparse, although the above assumption might still be found reasonable due to various offsetting factors. Only two general design parameters for infiltration facilities would be considered: storage capacity, and the percentage of impervious surface in a development which drains into these facilities. (It is assumed that no pervious land is drained into infiltration devices.) Based on an assumed value of the latter parameter, an estimate of required storage capacity would be obtained using a methodology developed for EPA by Hydroscience (forthcoming report).

The Hydroscience methodology deals with three generic types of treatment devices: (1) flow removal devices, (2) volume removal devices, and (3) flow proportional removal devices. Conceptually, an infiltration facility could be considered as either a flow removal device or a volume removal device. The latter is thought to be more appropriate here under present assumptions. A volume removal device is a facility which retains runoff up to a volume "V," and bypasses all remaining flow. The Hydroscience materials permit computation of the proportion of annual runoff which is captured by such a facility, as a function of storage capacity.

The graph developed by Hydroscience is based on the assumption that the storage area is always empty at the start of a storm event. In order to compensate for this assumption, as well as to simplify the design problem for infiltration facilities, the procedure adopted might make no allowance for infiltration achieved during storm events (which would allow re-use of storage capacity within a given storm). An infiltration device would thus be represented as a facility which captures runoff up to a volume V, holds this water for the duration of the storm, and transfers it completely to the soil at the end of rainfall. This assumption makes it unnecessary to consider explicitly the areal extent of the interface between the water storage area and the surrounding soil. The only design parameter considered explicitly would thus be the storage capacity of the device. (This would be equal to the volume of the storage chamber, if underground, times the porosity of the material occupying the chamber.)

The suggested procedure is demonstrated in Table 12, using the example of a 30% impervious development with half of all impervious surface draining into infiltration devices. This

TABLE 12

SAMPLE COMPUTATION OF STORAGE CAPACITY IN INFILTRATION DEVICES FOR NEW DEVELOPMENT

Land Characteristics

A.	Annual rainfall:	3.33 acre-feet/acre
B.	Number of storm events per year (days with rainfall ≥ 0.10 inch):	80
C.	Annual net infiltration (infiltration minus evapotranspiration) before development:	0.83 acre-feet/acre

Development Characteristics

D.	Proportion of land area covered by impervious surface:	0.30
E.	Percent of impervious surface draining into infiltration devices:	50%
F.	Proportion of land area consisting of impervious surface draining into infiltration devices (= D times E):	0.15
G.	Runoff coefficient for impervious surfaces:	0.9

Derived Variables

H.	Required infiltration to be achieved by devices (= C times D):	0.25 acre-feet/acre
I.	Required infiltration, relative to land draining into devices (= H/F):	1.67 acre-feet/acre
J.	Annual runoff from land draining into devices (= A times G):	3.00 acre-feet/acre
K.	Required proportion of runoff to be retained by devices (= I/J):	0.56
L.	Required volume of storage relative to runoff volume in average storm (from Hydroscience, based on item K):	1.25
M.	Required storage volume per acre of land draining into infiltration devices (= L times J/B):	0.047 acre-feet/acre
N.	Required storage volume, per acre of land in whole development site (= M times F):	0.007 acre-feet/acre

Source: Betz Environmental Engineers

could be a single-family housing development with infiltration devices designed to serve only rooftops, patios and parts of driveways. Annual rainfall is assumed equal to 40 inches (3.33 acre-feet per acre), with one-fourth of this quantity contributing to net infiltration under natural conditions. Construction of the development is assumed to reduce net infiltration by an amount proportional to impervious coverage. This reduction works out to 0.25 acre-feet per acre of land in the development. Determination of the storage capacity in infiltration devices needed to retain this volume of runoff on an annual basis is illustrated in steps I through M of Table 12. The key quantity is the ratio of required infiltration (annual retention of runoff in the devices) to annual runoff from land draining into the devices. This quantity is applied to the Hydroscience graph to obtain required storage capacity, as a proportion of the average runoff per storm event.

In the example shown, the required storage capacity of infiltration devices works out to 0.047 acre-feet per acre of land draining into the devices, or 0.007 acre-feet per acre of land in the development as a whole. It is apparent that this requirement is fairly modest. For example, if the development involves 1/4-acre house lots, adequate infiltration facilities could consist of a gravel-filled trench 3 feet deep (excluding earth cover), 2 feet wide, and 26 feet long on each lot. (This assumes a gravel porosity of 0.5.) Construction of these devices and associated drainage facilities would increase total development cost by only a very small percentage.

The overall procedure which is recommended here for promoting the use of infiltration measures would be to develop general guidelines for an entire study area or watershed. Various values would be assumed for imperviousness and percent of impervious surface draining into infiltration devices. Storage capacity requirements would then be computed as a function of these variables, using the Hydroscience methodology and regional values of annual rainfall, rainfall distribution over storm events, and infiltration minus evapotranspiration. The resulting tabulations would be made available as reference materials to local governments and other enforcement agencies. Review of development proposals by the latter would then involve: (1) comparison of storage capacity with the recommended amount indicated by the tables; and (2) verification that the design of each device will allow the water storage area to empty within a reasonable length of time, and that bypass water is handled adequately.

It is recognized that, due to the role of imported water, implementation of infiltration controls in this fashion could produce situations in which groundwater recharge is increased by new urban development. Nevertheless, the controls are still considered justifiable, in view of the greater demands for water use which will result from new development. An impact of urbanization which is extremely important is the increased demand for waste assimilative capacity in receiving waters. Increased groundwater recharge, resulting in higher base flow of streams, could be justified on these grounds alone.

It is clear that infiltration devices can achieve major reductions in stormwater pollutant loadings. For storms which do not exceed the design storage capacity, infiltration devices are potentially 100% effective in retaining pollutants from the areas served; and the percentage removal should be high even for larger storms, due to capture of the "first-flush" effect. If reduction in stormwater pollutant loadings is the primary objective of infiltration devices, the facilities would presumably be designed to serve all impervious surfaces in a developed area, or at least those surfaces most likely to contain pollutants. (One problem is that it is relatively difficult to serve street surfaces, which are thought to contain the largest quantities of pollutants, due to the safety factors involved in street drainage.) The effectiveness of infiltration devices in reducing stormwater pollutant loadings can be evaluated using another Hydroscience methodology, which takes account of variation in pollutant concentrations over time. Values of two parameters describing this variation are assumed; the percentage removal of pollutant loadings is then obtained by reading a value off a curve as before. (The relevant figure is entitled: "Fraction of Runoff Loading Rate not Retained".) The reduction in pollutant loadings is generally greater on a percentage basis than the reduction in stormwater volume, due to the inverse correlation between pollutant concentrations and time since start of storm.

A major unresolved issue is whether the use of infiltration devices for control of stormwater pollution runs the risk of contaminating the groundwater. Some proportion of the stormwater pollutants which pass through infiltration devices may reach the water table, and eventually reach surface waters, rather than being filtered out by the soil. This would not appear to be a major problem for sediment, phosphorus, or oxygen-demanding material in stormwater. Nitrate is rather likely to reach the water table, but may not be highly important since impervious surfaces do not tend to be dominant sources of nitrate. Salinity, resulting from the use of de-icing compounds, could definitely be a factor. The major question marks are heavy metals and perhaps pathogens. Delivery of the former to groundwater supplies could have serious long-term effects, although the probability of this occurrence due to infiltration devices is unknown.

On the other hand, agencies might prefer to face the possibility that contaminants are present in groundwater within a limited area, than to know for sure that they are in the stream. Infiltration devices are thus considered here to be a legitimate and perhaps highly favorable means of reducing stormwater pollutant loadings but should be designed for this purpose only if: (1) the bottom surface of each device is situated at least several feet above the seasonal high water table, and (2) there is no withdrawal of groundwater in the vicinity for domestic or other use. These conditions could well be met in many medium-density urban areas.

When infiltration devices are designed to serve impervious surfaces with large contaminant loadings, a potential problem is that particulate material could clog the device, thus necessitating frequent rehabilitation. A necessary step in such situations may be to provide a polishing pond in addition to the infiltration device itself. Most of the particulate material present would hopefully settle out before water is presented for infiltration. This step might allow reduction or even elimination of storage capacity in the infiltration device per se, but would complicate the overall facility, and might tend to offset the advantages of infiltration devices relative to stormwater retention and/or treatment.

In cases where reduction of pollutant loadings is not the primary objective, infiltration devices may be best applied to runoff from rooftops and paved areas which are not intensively used. Even so, rehabilitation of facilities may be necessary at long intervals. This would involve exposure of the storage area, if underground, and washing or sorting of the porous material used to provide storage capacity.

A major advantage of infiltration devices is that they can be invisible, as well as automatic in operation. If properly designed, infiltration facilities need not affect the land contour or vegetative cover (i.e., grass), although maintenance of vegetation may require placement of an impermeable shield over the storage area in order to prevent overly rapid drainage of the overlying soil. The use of these devices may place considerable constraints on development design, however. Each individual facility can ordinarily serve only a fairly small impervious surface, and should be located some distance from building foundations and other areas where soil wetness may be a problem.

The infiltration capacity of soils may also be a limiting factor. Infiltration devices should ordinarily be located above the seasonal high water table, in soils which are at least moderately permeable. Soil requirements should perhaps not be interpreted too stringently, given the facts that: (1) infiltration devices tend to work best when they are needed most, i.e., during dry weather; and (2) poor performance of infiltration devices during wet periods need not create special runoff problems if bypass is handled adequately. Although it clearly makes little sense to provide these facilities in cases where they do not produce significant benefits on a long-term basis, the possibility of their use should at least be considered for all new development, especially residential development.

SECTION 10

ASSESSMENT AND CONTROL OF ON-LOT DISPOSAL SYSTEM PROBLEMS

Introduction

On-lot disposal systems (OLDS) receive the wastewater from approximately 29% of the housing units in the United States. Nearly 20 million year-round housing units, occupied by roughly 58 million people, are served by OLDS. Of those people served by OLDS, 34 million live outside standard metropolitan statistical areas (SMSAs) and 25 million live inside SMSAs. Of the latter, 2.5 million live in central cities (Salvato, 1975). Thus, the use of OLDS is not limited to rural areas. OLDS also serve vacation homes, hotels, motels, camps, tent and travel trailer facilities, restaurants, gas stations, and other commercial properties.

An OLDS, for purpose of this discussion, includes any system or combination of systems which: (1) is currently receiving or is designed to receive wastewater from individual dwellings or establishments; (2) is designed to provide some degree of treatment for these wastewaters; and (3) discharges an effluent to the soil where further renovation of the effluent is expected to occur. Examples of OLDS include, but are not limited to:

septic tank - drain field
septic tank - seepage pit
cesspool
aerobic system - drain field
septic tank - alternate disposal system

Not included in the OLDS category are package treatment plants or lagoon systems (unless these systems use the soil for effluent renovation) and spray irrigation systems.

Because OLDS are being utilized for wastewater treatment in many rapidly developing areas, a generalized methodology may be needed to evaluate their existing and potential impact on water quality. The present section discusses various approaches which could be utilized.

The Problem - OLDS Impact on Water Quality

Many people believe that only those OLDS which are malfunctioning cause water pollution. While malfunctioning OLDS have significantly greater impact on water quality than properly operating systems, the latter can contribute to groundwater quality degradation.* Figure 13 schematically illustrates some of the water quality problems associated with OLDS. The major causes of OLDS malfunctions are: (1) improper system design or installation; (2) improper use; and (3) inadequate maintenance. With regard to the first item, a vast majority of system failures are caused by installing an OLDS in soils which are not physically or chemically suited for renovation of wastewater. Soils may be unsuitable for OLDS due to the following factors.

1. Insufficient or excessive drainage
2. Insufficient thickness to limiting layer
3. Poor gradation (i.e., rocky)
4. Presence of a seasonally or permanently high water table
5. Excessive slope

Even under ideal soil conditions for an OLDS, a system may be doomed to failure because of lax construction and inspection practices, or the use of inferior construction materials. Improper use of OLDS can cause sudden or gradual malfunctioning of the system. The two major categories of improper use are: (1) admission of extraneous water to the system (i.e., downspouts, sump pump, etc.); and (2) use of incompatible chemicals which harm or destroy the biological balance in the system (petroleum, oils, solvents, and harsh household chemicals such as sodium sulfate). Finally,

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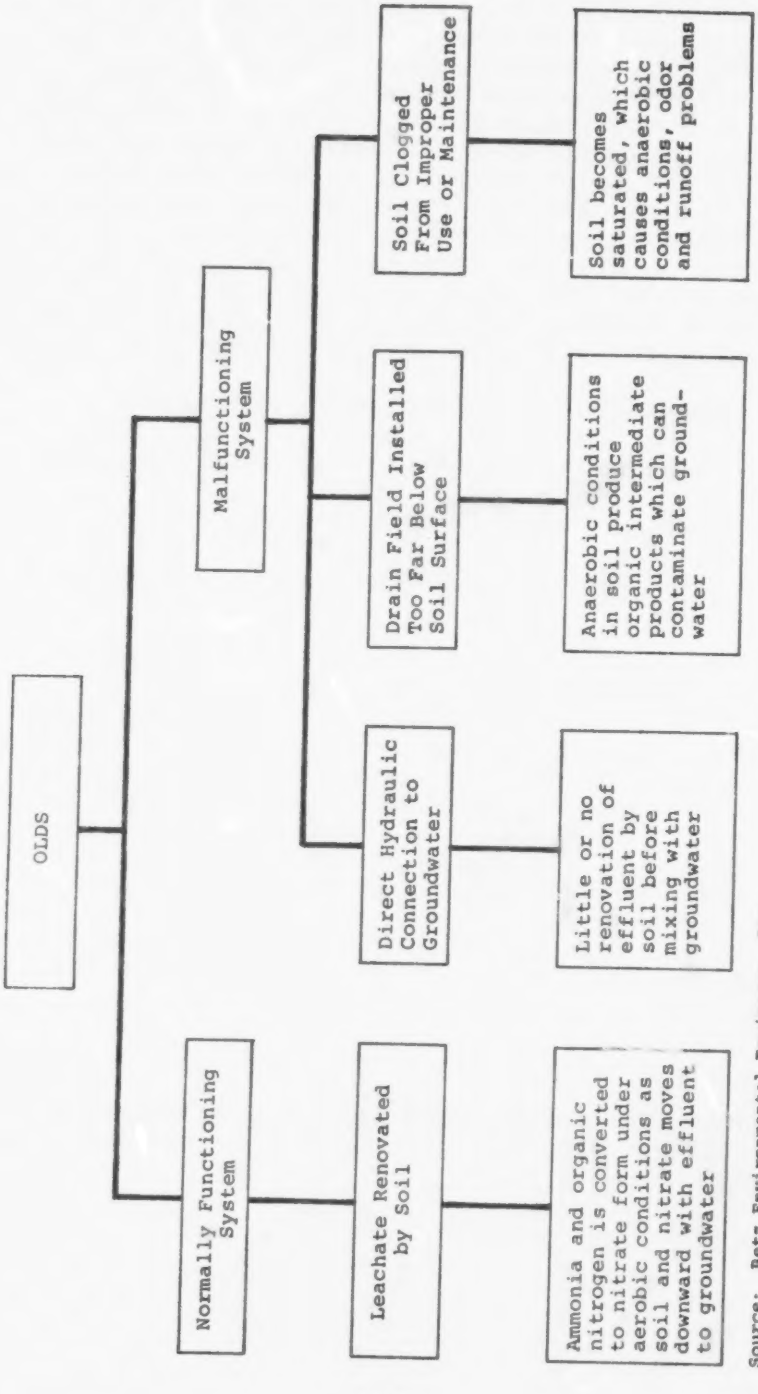
* This generally occurs when septic tank concentrations are too dense and proper dilution of tile field drainage is not achieved.


OLDS
Normally Functioning System
Malfunctioning System
Leachate Renovated by Soil
Direct Hydraulic Connection to Groundwater
Drain Field Installed Too Far Below Soil Surface
Soil Clogged From Improper Use or Maintenance
Ammonia and organic nitrogen is converted to nitrate form under aerobic conditions as soil and nitrate moves downward with effluent to groundwater
Little or no renovation of effluent by soil before mixing with groundwater
Anaerobic conditions in soil produce organic intermediate products which can contaminate groundwater
Soil becomes saturated, which causes anaerobic conditions, odor and runoff problems

Source: Betz Environmental Engineers, Inc.

Figure 13 SUMMARY OF OLDS IMPACT ON WATER QUALITY

problems due to lack of maintenance generally involve failure to remove periodically the accumulated sludge from the system.

OLDS Effect on Surface Water Quality

Impact of OLDS on surface water quality can involve either direct surface discharge to receiving waters, or outflow of groundwater which has been contaminated by on-lot systems. Direct discharge of OLDS effluent to surface watercourses usually results from a hydraulic failure of the soil absorption portion of the system (seepage bed, tile field, etc.). Wastewater applied to the seepage bed or tile field must go somewhere; when it can no longer percolate through the soil, it surfaces and flows to the nearest drainageway. Other, less common causes of system failure to the surface include broken or crushed distribution lines, and blockage of lines by accumulated solids or root intrusions. Overflow of an OLDS to a surface watercourse is, from a water quality standpoint, similar to raw sewage discharge to that watercourse. Table 13 compares average concentrations of several parameters in a medium-strength raw sewage to an average septic tank effluent.

Effects on surface water quality due to outflow of groundwater can be produced by normally functioning OLDS as well as malfunctioning systems. The mechanisms involved are the same as those discussed below for groundwater contamination. For normally functioning systems which are well-located with regard to water quality, the surface water effects tend to be limited to nitrate and various dissolved solids of lesser importance. In other cases, the pollutants delivered to surface waters by way of groundwater can also include phosphate, pathogens, and oxygen-demanding material.

In regions where OLDS impact on surface waters is a major issue, it may be helpful to develop generalized relationships which can be used to predict the impact of this factor over large areas. Evidence suggests that such relationships can be successfully obtained from empirical studies, under at least some circumstances, if steps are taken to control for soil characteristics and land uses other than development served by OLDS. The procedure is to monitor surface water quality in basins (usually small) in which OLDS are clearly the predominant influence on water quality other than "background" pollutant loadings. Careful design of the

TABLE 13

COMPARISON OF CHARACTERISTICS OF RAW SEWAGE AND SEPTIC TANK EFFLUENT

	Concentration in mg/l	
Parameter	Medium Strength Raw Sewage (1)	Septic Tank Effluent
Suspended Solids	200	140 - 150 (2)
BOD_5	200	100 - 120 (3)
COD	500	360 (3)
NH_3-N	25	35 (4)
Organic N	15	10 (4)
Total P	10	25 (4)
Bacteria	--	12,000/ml (5)

Sources:

(1) Metcalf and Eddy, 1972

(2) Harkin, 1976

(3) Kreissel, 1976

(4) Dudley and Stephenson, 1973

(5) Harkin, 1976

sampling program may allow estimation of relationships between OLDS pollutant loadings and hydrologic conditions, as well as relationships involving the density, location, and characteristics of on-lot systems.

One example of such a study is a recent investigation of OLDS impact on surface water quality in Chester County, Pennsylvania (Howard and Hammer, 1973). The basins studied in this case contained primarily housing units less than 30 years old, at various densities. Soils were moderately-permeable and generally considered suitable for on-lot disposal. The observed pattern of relationships between pollutant concentrations and density of on-lot disposal systems was the following.

Significant Relationships with OLDS Observed

Nitrate
Total nitrogen
Chloride
Calcium
Magnesium
Sodium
Total dissolved solids (3 measures)
Total coliform bacteria
Fecal streptococcus bacteria

No Significant Relationships Observed

Dissolved oxygen
COD
Organic nitrogen
Ammonia
Ortho phosphate
Total phosphate
Potassium
Bicarbonate
Iron
Fecal coliform bacteria
pH

The predictive equations obtained, which attributed very large effects to OLDS in some cases, were generally consistent with expectations. It is likely that greater effects would have been observed for some constituents, such as phosphate, if soil conditions in the study area had been less favorable for OLDS. An important finding of the study was that bacterial contamination of surface waters was highly sensitive to the existence of OLDS within 100 feet of streams and swales (the latter of which could largely be considered perennial watercourses). Thus, in analytical and planning activities it may be essential to consider the location of OLDS with respect to surface waters, as well as with respect to land features such as soils, geology, and slope. Development of empirical relationships in this fashion requires considerable effort, in terms of water quality sampling and measurement of basin characteristics.

(The latter must frequently be expressed in terms of interaction variables, i.e., number of OLDS located on land in various categories.) Nevertheless, estimation of such relationships may be worthwhile, given that the multiplicity of OLDS tends to limit treatment of this factor on a site-specific basis.

OLDS Effect on Groundwater Quality

The influence of OLDS on groundwater quality is dependent primarily upon the following factors.

1. OLDS density in an area
2. Type, number, and degree of malfunctioning OLDS
3. Amount of rainfall and groundwater available for dilution of effluent (i.e., groundwater flow, quantity, and direction)
4. Hydraulic and chemical characteristics of soil, subsoil, and aquifers

Figure 13 indicates that the greatest potential for groundwater contamination from OLDS results from direct hydraulic connections (gravel or solution channels) between the drain field or cesspool and groundwater. This type of problem results in direct recharge of effluent, with little or no renovation, to the groundwater. In an aquifer containing numerous fractures, faults or solution channels, the effluent can travel with the groundwater for distances ranging from less than one hundred feet to several miles. Wells located a considerable distance away from the malfunctioning OLDS, in the direction of groundwater flow, can therefore be contaminated. This situation probably represents the most severe groundwater contamination problem associated with OLDS. Another potential problem is that drain fields which have been installed too deep in the soil develop anaerobic conditions and can contribute products of anaerobic decomposition. These products include bacteria and viruses, undegraded detergents, and partially decomposed organic compounds which can contaminate groundwater and surface water.

Perhaps the most difficult impacts to assess are those produced by properly operating OLDS on groundwater quality. A well-drained soil with an adequately designed and properly installed effluent disposal field is capable of providing an adequate oxygen supply for reduction of BOD and COD (Miller and Wolf, 1975). An important aspect of OLDS operation is mineralization of organic nitrogen and ammonia nitrogen (NH3) to the nitrate form (NO3) in the presence of oxygen. If septic tank systems are situated in areas having well-drained soils and relatively deep water tables, NO3 is the nitrogen product of primary concern after renovation of septic tank effluent by the soil (Holzer, 1975). Numerous authors have addressed in detail the nitrogen transformations which take place in various components of OLDS (Hall, 1975; Holzer, 1975; Miller and Wolf, 1975; and Walker, et al, 1973).

Because NO3 is an anion and is extremely soluble in water, the cation exchange capacity (CEC) of soil is not effective in adsorbing NO3. Consequently, the NO3 moves with percolating OLDS effluent to the groundwater. Indications are that, although some denitrification (conversion of NO3 to NO2 or nitrogen gas under anaerobic conditions) may occur in fine-textured, well-structured subsoils, the NO3 concentration (as N) of the percolate from a seepage bed generally approximates the total N concentration of a septic tank effluent (Sikora and Keeney, 1975).

Disposal of human wastes in a soil system can present a potential public health hazard due to the admission of pathogenic organisms into the groundwater supply. The magnitude of the hazard depends on the presence, quantity and accessibility of the pathogens. Prediction of this problem is difficult since various physical, chemical and microbiological properties of the soil have the ability to render pathogenic organisms nontoxic. In general, the soil presents a hostile environment to most pathogenic organisms. (Pathogen survival times in soils have been summarized by Miller and Wolf, 1975.)

Pathogen movement in soil systems by percolation has been studied extensively and appears to be related to soil type and hydraulic considerations (Miller and Wolf, 1975). Two important factors are the size of the pathogen relative to the pore sizes within the soil, and the adsorption processes which are operative. Under favorable conditions, pathogen movement through soils tends to be sufficiently restricted that a minimal public health hazard is presented. However, as previously indicated, severe contamination can be produced by OLDS which have direct hydraulic connections (via faults, fractures or solution channels) with the groundwater.

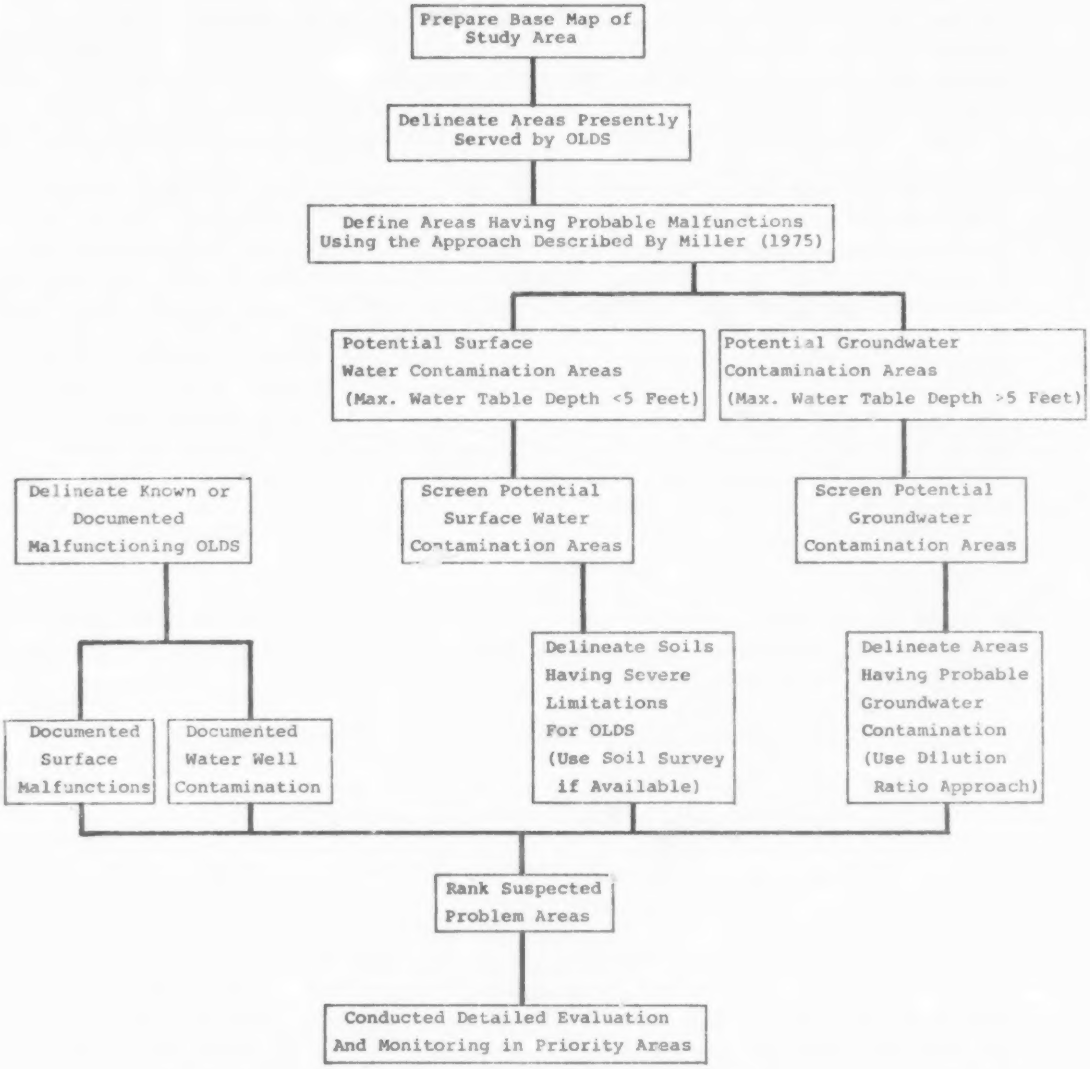
Delineating OLDS Impact on Water Quality

The following discussion describes a mapping technique for delineation of present and potential OLDS problems which does not rely heavily upon water quality data. The procedure is outlined schematically in Figure 14. Since mapping is involved, a good quality base map of the study area is required. U.S. Geological Survey quadrangle sheets (7-1/2-minute series) are ordinarily suitable for this purpose. Areas presently served by OLDS should be delineated on an overlay of the base map. This information is generally available from: municipal wastewater facilities planning studies, municipal sewer system records, county health department records, or state regulatory agency files and records.

An important task is to delineate land areas where OLDS malfunctions are likely to occur. Following an approach suggested by Miller (1975), areas of probable OLDS malfunction are designated "potential surface water contamination areas;" and other land areas are designated "potential groundwater contamination areas." (It is understood that malfunctioning OLDS can also cause groundwater pollution, and that properly operating systems can affect surface water quality to some degree, as noted earlier.) Delineation of these two categories of land is based upon soil characteristics. The following characteristics are relevant:

drainage
depth to bedrock
slope
presence or absence of seasonally high groundwater table
texture
presence of faults, fractures, or solution channels in underlying geologic formations

The best sources of detailed soil information are the U.S. Department of Agriculture (USDA) Soil Survey Reports. These reports have been prepared for many counties throughout the country. In many of the USDA reports, the above characteristics have been considered for each soil series in order to


Prepare Base Map of Study Area
Delineate Areas Presently Served by OLDS
Define Areas Having Probable Malfunctions Using the Approach Described By Miller (1975)
Potential Surface Water Contamination Areas (Max. Water Table Depth <5 Feet)
Potential Groundwater Contamination Areas (Max. Water Table Depth >5 Feet)
Delineate Known or Documented Malfunctioning OLDS
Screen Potential Surface Water Contamination Areas
Screen Potential Groundwater Contamination Areas
Documented Surface Malfunctions
Documented Water Well Contamination
Delineate Soils Having Severe Limitations For OLDS (Use Soil Survey if Available)
Delineate Areas Having Probable Groundwater Contamination (Use Dilution Ratio Approach)
Rank Suspected Problem Areas
Conducted Detailed Evaluation And Monitoring in Priority Areas

Source: Betz Environmental Engineers, Inc.

Figure 14 SCHEMATIC DIAGRAM OF OLDS WATER QUALITY IMPACT EVALUATION

estimate the degree of limitation for OLDS. This information is usually presented in a table entitled "Major Soil Properties and Estimated Degree of Limitation that Influence Use of Soils for Community Developments" (USDA, 1967). Soil limitations for OLDS are classified as "slight," "moderate," or "severe." When detailed Soil Survey data are available, it is possible to proceed directly through several of the steps shown in Figure 14 by mapping the soil series designated as having severe limitations for OLDS. (It may be convenient simply to use the USDA soil maps as base maps, rather than transferring soils information to other maps.)

When detailed USDA surveys are not available, other steps are necessary to determine potential surface water contamination areas. The hydrogeologic approach suggested by Miller (1975) involves a distinction between areas having a maximum groundwater table less than five feet below the land surface, and areas in which the water table is always more than five feet below the surface. Water table depth is a good predictor of hydraulic failure of OLDS; areas in which the maximum depth is less than five feet are therefore selected as potential surface water contamination areas. Groundwater contamination, primarily involving nitrate, is most likely to occur where soils are permeable and/or well-drained, in which case the water table is normally well below the land surface.

A number of sources of hydrogeologic information are available which would permit delineation of the five-foot groundwater depth contour. These include:

U.S. Geologic Survey Hydrologic Investigations Atlas
    Series
U.S. Geological Survey Professional Papers
State Geologist's records and reports

Having established regions of potential surface water and groundwater contamination, further screening of problem areas is conducted utilizing different approaches in the two cases. Surface water problem areas are isolated through further examination of soils information, including all of the characteristics listed above. An additional factor which is likely to be important, as noted elsewhere, is hillslope position. The distance of land to a stream or swale is correlated with water table depth, and frequently is associated with soil characteristics that are relevant to

OLDS performance (due to the presence of alluvial soils near streams). Thus, OLDS which are situated near the bottom of hillslopes are relatively likely to affect surface waters through both surface and subsurface flows. When attempting to isolate surface water problem areas, the only available soils information may pertain to soil associations rather than soil series. Care must be taken in interpreting soil association descriptions since these data are usually very general, and in practice may not add significantly to the information already conveyed by the five-foot groundwater depth contour.

Analysis of groundwater problems due to OLDS in areas where water table depth is not an issue should consider three possible causal factors: (1) overly rapid percolation, which would allow unrenovated OLDS effluent to reach the saturated zone; (2) improper location of wells; and (3) excessive density of OLDS. The first two factors must often be examined on a site-specific basis, using geologic data and/ or field inspection. The density question, involving either existing or potential OLDS, can be examined using methods based on the dilution ratio concept. The question is whether renovated OLDS effluent is receiving adequate dilution in the groundwater. Dilution of the effluent by uncontaminated groundwater is the principal means of decreasing the concentration of solutes, primarily NO3, in the effluent.

The dilution ratio may be defined as the ratio of the quantity of percolating effluent per unit area to the net groundwater recharge per unit area. In equation form:

$$\text{Dilution Ratio} = \frac{Q\ (\text{effluent})}{Q\ (\text{net recharge})}$$

Net recharge is water reaching the surficial aquifer (the same aquifer receiving OLDS effluent) which is available for dilution of OLDS effluent. Net recharge is equal to infiltration minus groundwater evapotranspiration losses and groundwater withdrawals via wells tapping the surficial aquifer.

On the assumption that nitrate is the primary anion of concern in properly renovated OLDS effluent, Holzer (1973) has concluded that net groundwater recharge must achieve at least a one-to-one dilution of OLDS effluent, in order for groundwater conditions to be acceptable.

> "Based on the concentrations of nitrate measured by Bouma et al, 1972, and Miller, 1972, a dilution of renovated effluent of at least one-to-one may be required to reduce nitrate concentrations to the public health standard of 45 mg/l NO_3 in permeable soils with deep water tables." (Holzer, 1973).

The dilution ratio can be applied in two ways: (1) the net aquifer recharge rate approach; and (2) the aquifer cross-sectional approach. Only in the first case is it necessary to determine the net aquifer recharge rate for an area of land. This can be done using any technique which provides an accurate water balance of the surficial aquifer. Factors to consider include:

1. Total annual recharge from precipitation (usually expressed in inches)

2. Total annual withdrawals via wells from the surficial aquifer

3. Groundwater evapotranspiration

An alternative is to determine net recharge for large areas using surface water gaging records. (See the discussion of infiltration devices in the previous section.) On an average basis, net groundwater recharge equals stream base flow, plus imported water, minus exported water.

The second method of applying the dilution ratio--the aquifer cross-sectional approach--is applied on a more detailed basis than the net aquifer recharge rate approach. The cross-sectional method assumes that any mixing of OLDS effluent with groundwater takes place in the upper five feet of the saturated zone (Dudley and Stephenson, 1973). Groundwater flow through a selected cross-section of aquifer may be computed using Darcy's Law:

$$Q = KIA$$

where:

Q = flow through upper 5 feet of aquifer (gal/day)

K = aquifer permeability (gal/day/ft. sq.)

I = hydraulic gradient (ft/ft)

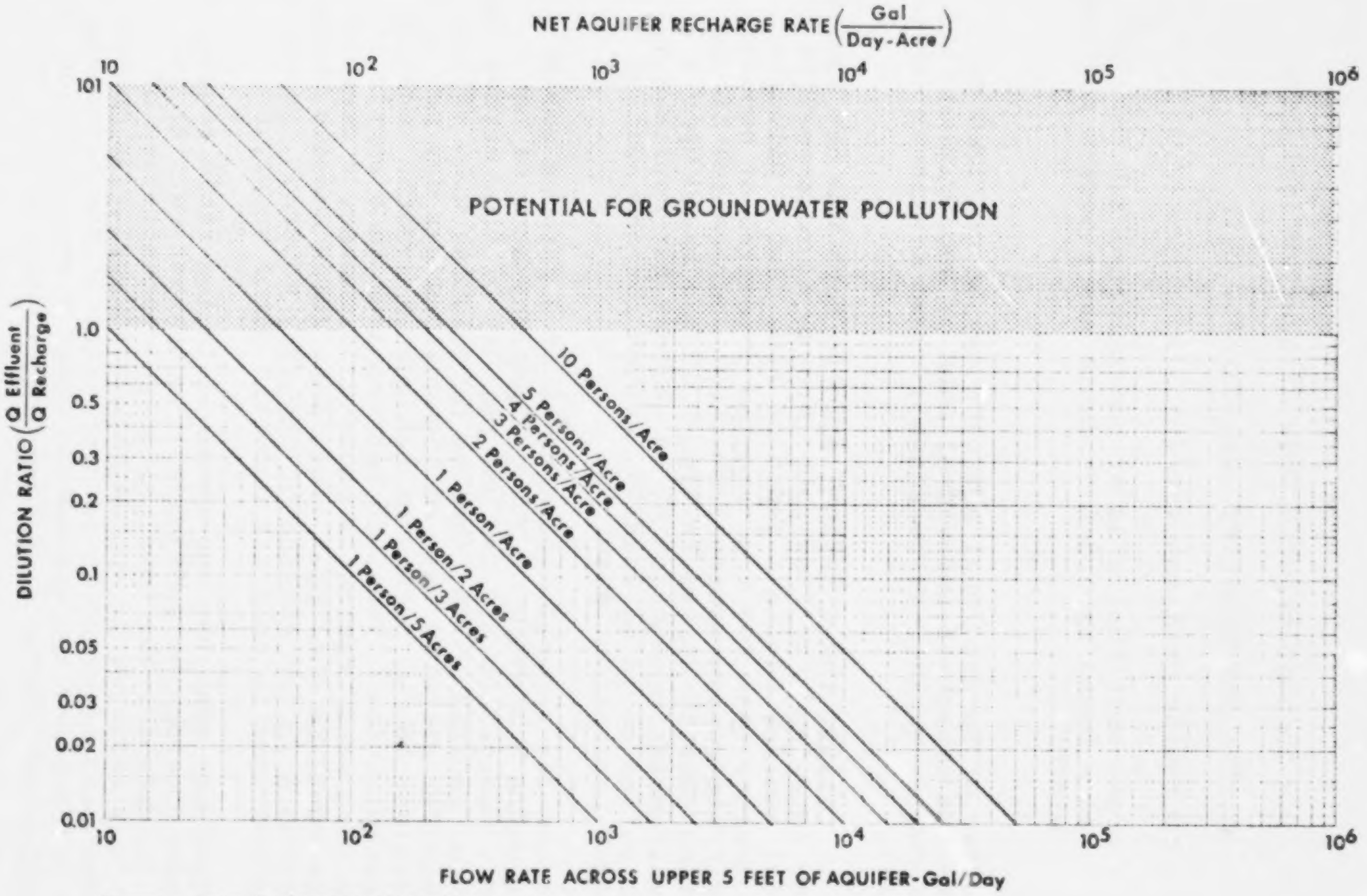
A = cross-sectional area of contaminated aquifer (ft. sq.--based upon 5-foot depth and selected section width)

The aquifer cross-sectional approach may be utilized to estimate the impact of individual OLDS or subdivision OLDS on groundwater quality at reasonably close distances (up to 1/4 mile).

Figure 15 relates the dilution ratio to both the net aquifer recharge rate, and the flow rate through a cross-section of surficial aquifer having a depth of five feet. Dilution ratios greater than 1.0 indicate the potential of groundwater nitrate contamination from OLDS. Derivation of the population density curves in Figure 15 was based upon a daily wastewater production of 50 gallons per capita-day. Similar curves could be readily derived for any desired wastewater production value.

From Figure 15, a population density of 3 persons per acre would require a minimum of 150 gallons/day/acre of net aquifer recharge, or 150 gallons per day of flow across the section of aquifer which receives percolating OLDS effluent. A net aquifer recharge rate of 150 gallons per day per acre is equivalent to 2.0 inches of net annual aquifer recharge from precipitation. Thus, if net recharge in a particular portion of a study region is equal to 2 inches, 3 persons per acre would be the upper limit population density which is acceptable in the absence of sanitary sewerage, assuming that groundwater is used for domestic water supply.

It is possible that the one-to-one dilution ratio suggested by Holzman may not be sufficiently conservative. As indicated in Table 13, the total nitrogen concentration of septic tank effluent is approximately 45 mg/l. In general, the total nitrate-nitrogen concentration of the percolate from a seepage bed approaches the total N concentration of the septic tank effluent (Sikora and Keeney, 1975). This



Source: Betz Environmental Engineers, Inc.

Figure 15 DILUTION RATIO ANALYSIS

translates to approximately 200 mg/l as NO3. Thus, in order to attain a nitrate concentration in groundwater of 45 mg/l, as NO3, a dilution ratio as low as 0.29 could be required (equal to 45/(200-45)). Referring again to Figure 15, this criterion would indicate that a population density of 3 persons per acre would require slightly more than 500 gallons/day/acre of net aquifer recharge, or about 7 inches on an annual basis.

A final step in mapping OLDS impact on water quality is to delineate areas where OLDS malfunctions have been documented. Sources of information about malfunctioning OLDS include:

1. State health or regulatory agency files
2. County health department records
3. Municipal health department or engineer's records

Nearly all documented malfunctions will probably be surface malfunctions, which have been recorded because of complaints about odor and unsightly conditions. In some cases, documentation of well water contamination from OLDS may be found and should provide insight into groundwater flow patterns in the area. Care must be taken to determine the cause of malfunction before the defective OLDS is delineated on the study area map. System failure due to misuse or lack of maintenance does not necessarily reflect soil or geologic conditions in the area.

Control of OLDS Problems

The existing problem areas thus identified would be ranked in importance, and subjected to detailed study if possible through detailed monitoring activities. Remedial measures would then be designed on the basis of the findings obtained. These measures might include:

1. Conventional repairs to existing systems (e.g., moving absorption field).
2. Install alternate or experimental systems (e.g., aerobic treatment systems, elevated sand mound, evapotranspiral beds).

3. Renovate and maintain absorption area permeability via peroxide treatments (see: Harkin, Jawson, and Baker, 1975).

It is important to acknowledge that existing OLDS problems are often legal and institutional in origin rather than strictly technical. Government authority tends to be fragmented, with various roles assigned to city, county, regional, and state agencies. Often there are no specific criteria or standards which clearly define system failure, and no specific programs to assure that systems are being properly maintained. Agencies generally do not possess adequate manpower to conduct the monitoring and enforcement activities implied by such a program. Thus, perhaps the most important step in correcting existing OLDS problems, once identified, is to effect the necessary institutional changes.

With regard to the location and design of new OLDS, it is likely that ultimate determinations will continue to be made on a site-specific basis, through the use of percolation tests. Delineation of potential problem areas on a regional basis as part of current studies is nevertheless valuable, in order to integrate OLDS permitting activities with public facility planning and land use planning. The important question is how to deal with areas in which soils are generally unsuitable for OLDS use. The following options are available in planning for such districts.

1. Discourage development through public improvements planning. Highways and other facilities which encourage urban growth can perhaps be planned on a regional basis so that new development involving OLDS is directed away from inherently unsuitable areas.

2. Establish protection districts. Development can be limited in undesirable areas by establishing protection districts through such mechanisms as zoning, conservation easements, and land purchase. Areas unsuitable for OLDS might be given high priority for open space uses.

3. Provide centralized sewage disposal. Within the area which is unsuitable for OLDS use, public sewerage can be provided to selected development districts (and package treatment plants might be

> allowed in these districts). When public sewerage is provided, a general reversal of strategy becomes appropriate: it is desirable to promote high-density development in order to absorb as much urban growth within the development district as possible; whereas low density is generally desirable when OLDS are utilized. One liability of establishing development districts within areas unsuitable for OLDS is that urban growth may tend to sprawl beyond the boundaries of the district. Thus, strict control of new OLDS permits becomes especially crucial.

On the whole, the situation that must be avoided is the circumstance which was typical in the past, wherein dwellings with OLDS were allowed to sprawl haphazardly across areas where soils were basically unsuitable, so that public sewerage was eventually required as a remedial measure. Sewer systems constructed in response to OLDS problems tend to be much more expensive and inefficient than systems which have been planned in an orderly fashion in anticipation of growth.

In the granting of individual OLDS permits it may be important to augment standard procedures in a number of respects. Percolation testing at multiple locations on a site and/or times of year may be advisable. Overly rapid percolation and overly slow percolation should be grounds for denial of permits. Local geologic information may also be consulted, for example, to avoid location of OLDS in areas underlain by limestone where problems would be created by rapid movement of unrenovated effluent through solution channels. Steps should be taken to avoid location of OLDS close to surface waters (e.g., within 100 feet), even if percolation tests are positive. This would apply to small headwater streams as well as major water bodies. Establishment of protection districts along all perennial or nearly perennial watercourses would be ideal; but important benefits can be gained by considering this factor on an ad hoc basis. In designing the type of system to be specified in a given OLDS permit, the full range of alternatives should be considered, including expensive designs such as elevated sand mounds and dual absorption fields. The overall objective of OLDS permitting activities should be to shift as much of the burden of water quality control to the design and construction stage, as opposed to later monitoring, surveillance, and remedial activities.

Establishment and implementation of appropriate institutional arrangements and regulatory programs for OLDS use tends to be a difficult task, requiring a careful balancing of objectives. On the one hand, in terms of water quality, every OLDS may be a liability. In most urban regions there are substantial water quality and health incentives to minimize OLDS use as much as possible. On the other hand, on-site sewage disposal may be essential for land development of any kind in many instances. Denial of permits can cause economic and social hardships for landowners and potential residents. The overall posture adopted within a municipality or other enforcement district should therefore reflect a weighting of the following factors: (1) existing problems due to OLDS; (2) variability of soils limitations for OLDS use, i.e., opportunities for development at locations where limitations are not severe; (3) existing use of groundwater and surface water; (4) probability that OLDS use will create increasing problems in the future; (5) ability of residents and potential residents to pay for elaborate disposal systems; and (6) extent to which OLDS use, as opposed to joint sewage disposal, is actually necessary to meet demands for housing and other facilities. Permitting agencies should attempt to establish their role in positive terms, assisting communities and individuals in developing adequate solutions to waste disposal problems, rather than appearing solely as an inhibiting influence on community development.

SECTION 11

EVALUATION AND CONTROL OF EROSION FROM CONSTRUCTION SITES

Introduction

Sediment produced by soil erosion is often considered to be the most important single pollutant from nonpoint sources. Sediment impairs water quality, chokes stream channels and reservoirs with deposits, and adversely affects aquatic life and the recreational value of water resources. In addition, sediment eroded from topsoil often carries large amounts of pollutants, such as nutrients, organic matter, pesticides, and pathogens. Erosion of soil by water can be categorized as follows:

- Surface Erosion
    - sheet erosion
    - rill erosion*
- Channel erosion
    - gully erosion
    - streambank erosion

The present section deals only with surface erosion, particularly soil loss from construction sites. The formulation which is most commonly used for evaluating sediment problems is the Universal Soil Loss Equation (USLE). As shown below, the USLE is a very simple relationship involving a series of multiplicative factors which denote influences upon soil loss. Over the past two decades, considerable experience has been gained in the use of this formulation, although the primary focus until recently has been erosion from agricultural land rather than construction sites. The advantages of the USLE as an analytical tool are its extreme flexibility, the familiarity of many persons with its use, and the fact that it relates directly to control measures.

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* Rill erosion is actually a form of minor channel erosion. For purposes of analysis, rill erosion is usually treated as sheet erosion.

The development and application of the USLE have been discussed at length in numerous references, most notably the comprehensive report on loading functions by Midwest Research Institute (McElroy *et al*, 1975). The present discussion will therefore be *limited* to a brief treatment of several conceptual issues, and presentation of a methodology incorporating the USLE which has been developed by Chen (1974).

The form of the Universal Soil Loss Equation is the following:

$$\text{SEDIMENT LOADING DUE TO SURFACE EROSION (TONS/ACRE/YEAR)} = R\ K\ LS\ C\ P\ Sd$$

where:

R = the rainfall factor, expressing the erosion potential of average annual rainfall. (R is a summation across storms of the kinetic energy of rainfall, in hundreds of foot-tons per acre, times the maximum 30 minute rainfall intensity in inches per hour);

K = the soil-erodibility factor, commonly expressed in tons per acre per R unit;

L = the slope-length factor (dimensionless);

S = the slope-steepness factor (dimensionless);

C = the cover factor (dimensionless);

P = the erosion control practice factor (dimensionless); and

Sd = the sediment delivery ratio.

The rainfall factor, R, is expressed here in terms of average annual conditions, but could relate to short-term conditions or even a single design storm. Annual values of R can also be selected which represent worst-case conditions rather than average conditions (e.g., the worst year in ten for erosion potential). Tabulations of R values applying to specific localities are available in numerous publications (McElroy, et al, 1975). K, the soil erodibility factor, is a property of specific soil types and has been tabulated in detail by the U.S. Soil Conservation Service. The factors L and S, pertaining to slope length and gradient, are commonly considered together. Tabulations are available for the quantity LS as a function of hillslope characteristics.

The sediment delivery ratio, Sd, represents the proportion of eroded soil which actually reaches a given point in the surface water system. For example, a sediment delivery ratio of 0.4 would mean that 40% of the soil lost from the land area under study would reach the given stream point, whereas the other 60% would settle out in stream channels and other locations. In cases where the USLE is used to predict sediment loadings from an entire basin, the value of Sd is intended to describe sediment delivery from the catchment as a whole. (Loadings are usually predicted in such cases by measuring the other terms of the USLE for subdivisions of the catchment, summing the products, and then applying the sediment delivery ratio.) Values of the sediment delivery ratio are highly dependent upon local conditions, and therefore tend to be difficult to predict accurately.

C and P, the cover factor and the erosion control practice factor, are the two elements of the USLE which express human influence on sediment yields. The appropriate values of C and P for agricultural land uses have been a subject of study for many years; but only recently have values been developed which apply to construction sites under various degrees of control. On the whole, the exercise of subjective judgment in applying the USLE centers largely around the parameters Sd, C, and P, although considerable information is now available for assistance (see below).

Behavior of Sediment Loadings

Before discussing the use of the USLE for planning purposes, some comments are offered regarding the general behavior of sediment loadings. It should be recognized that sediment

TABLE 14

ANALYSIS OF ANNUAL SEDIMENT YIELD FOR SMALL RURAL WATERSHEDS IN CHESTER COUNTY, PENNSYLVANIA

Stream Discharge, in cfs Per Square Mile of Watershed		Annual Duration of Discharge within the Given Range, in Days	Suspended Solids Loading	
Range	Ave. Value		Ave. Concentration in mg/l	Total Load in Tons/Sq. Mi.
1 - 1.99	1.4	104	20	8
2 - 9.99	4	37	87	34
10 - 19.99	14	1.3	227	11
20+	43	0.9	757	79
			Total Annual Load:	132

Source: Hammer, 1973, p. 139 (based on data from Miller, Troxell and Leopold, 1973)

TABLE 15

VALUES OF SEDIMENT DELIVERY RATIO FOR SMALL AGRICULTURAL BASINS IN TEXAS

Year	Computed Value of the Sediment Delivery Ratio (Dimensionless)				
Basin:	Y2	W1	Y	D	G
1962	0.23	0.24	0.24	0.16	0.18
1964	0.09	0.19	0.06	0.11	0.06
1965	1.26	0.80	0.86	0.84	0.45
1966	0.85	1.26	1.09	1.20	0.65
1967	0.06	0.13	0.07	0.09	0.12
1968	1.24	1.06	1.22	0.34	0.73
1969	0.16	0.12	0.33	0.38	0.38
1970	0.24	0.64	0.54	0.43	0.44
Overall SDR for 8 Years	0.67	0.63	0.66	0.48	0.42

Source: Williams & Bernadt, 1972

yields are very sensitive to hydrologic conditions and tend to be extremely concentrated in time. The latter fact is illustrated in Table 14, which is based upon suspended solids data for a number of rural watersheds in Chester County, Pennsylvania, ranging between 3 and 6 square miles in area. The time in a typical year is subdivided into five categories on the basis of stream discharge. (One category is not shown since it involves negligible suspended solids loadings.) For example, the second row indicates that stream discharge is between 2 and 10 cfs per square mile for a total elapsed time of 37 days per year; the average discharge under these conditions is 4 cfs per square mile. As shown in the fourth column, suspended solids concentrations bear an extremely strong positive relationship with discharge. The average concentration when discharge exceeds 20 cfs per square mile is nearly 40 times as great as the average when discharge is between 1 and 2 cfs per square mile.

The fifth column of Table 14 shows the total suspended solids yield associated with each range of discharge during a typical year. The total annual loading is 132 tons per square mile. The most striking fact is that well over half of this loading occurs during conditions which occupy only about one day's time out of the year. (These conditions account for slightly less than 10% of total annual runoff.) In spite of the fact that rainfall in southeastern Pennsylvania tends to be well-distributed throughout the year, it is apparent that half a year's loadings of suspended solids could occur during a single storm. This dominance of extreme events, and the fact that suspended solids concentrations are imperfectly related to discharge, often makes it difficult to compute suspended solids loadings accurately even when field data are available.

Some additional data relating more directly to the USLE are presented in Table 15. Five small agricultural basins in Texas were studied by Williams and Berndt (1972) during the 1962-1970 period. Values of the sediment delivery ratio were estimated for each basin in each year by dividing the observed sediment load by the estimated soil loss, where the latter was computed as the product of the factors R, K, LS, C, and P. This procedure treats the sediment delivery ratio as a "residual" term in the USLE--i.e., attributes any errors in the equation to the sediment delivery ratio.

The resulting estimates of the sediment delivery ratio for the five basins are presented in Table 15. The variability among the figures in each column is notable. For every basin, the highest computed value of the sediment delivery ratio over the eight years of record is at least ten times as great as the lowest value. (No storm runoff occurred in 1963.) These data do not necessarily demonstrate that sediment delivery per se varies over time; but indicate that there may be a substantial degree of error in the USLE as a whole. This circumstance is attributed by Williams and Berndt to three factors: (1) the small number of storms in each year; (2) variation in the grouping of storms (which affects antecedent soil moisture, and hence relates to runoff and erosion); and (3) a tendency of the USLE to overpredict sediment for years when the rainfall index R is low, and underpredict sediment for years with high values.

Such evidence suggests that sediment loadings are generally difficult to predict accurately, regardless of the methodology utilized. An even more difficult problem may be to estimate the effects of sediment on water use--for example, the impacts on aquatic biota. These points are not intended to discourage quantitative analysis of erosion and sedimentation problems, but simply to suggest the limitations of such analysis.

Quantitative Evaluation of Erosion Control Measures

The appropriate role of the USLE in planning studies depends somewhat upon the manner in which control measures are expected to apply--specifically, the extent to which controls will be tailored to the circumstances encountered at individual construction sites. At one extreme, the controls which are implemented may be relatively uniform across the study area, in that the physical measures required at construction sites do not vary greatly with the characteristics of the land or the receiving waters affected. At the other extreme, the required control measures could be geared to attainment of desired conditions in specific receiving water bodies, and/or might be strongly related to the erosion potential of land at the construction site. In the former case, use of the USLE might be limited to sample demonstrations of erosion magnitudes and the effectiveness of controls; whereas in the latter case the USLE would be integral to the planning process.

A convenient methodology for linking erosion/sedimentation controls to in-stream conditions and land characteristics has been developed by Chen (1974). This approach involves partitioning the total sediment load into two components: the loading from construction land, and the loading from non-construction land. Each of these loadings is equal to the per-acre soil loss from the given land type, times the acreage involved, times the overall sediment delivery ratio for the catchment under consideration.

Chen presents a "macro model" which could be used to determine the allowable rate of soil loss from construction lands, on the basis of allowable in-stream sediment concentrations. The macro model basically consists of a straightforward set of computations utilizing assumed values of soil loss from non-construction lands and the sediment delivery ratio. The latter could be estimated from sources such as Figure 16, which relates the sediment delivery ratio to drainage density and predominant soil type.

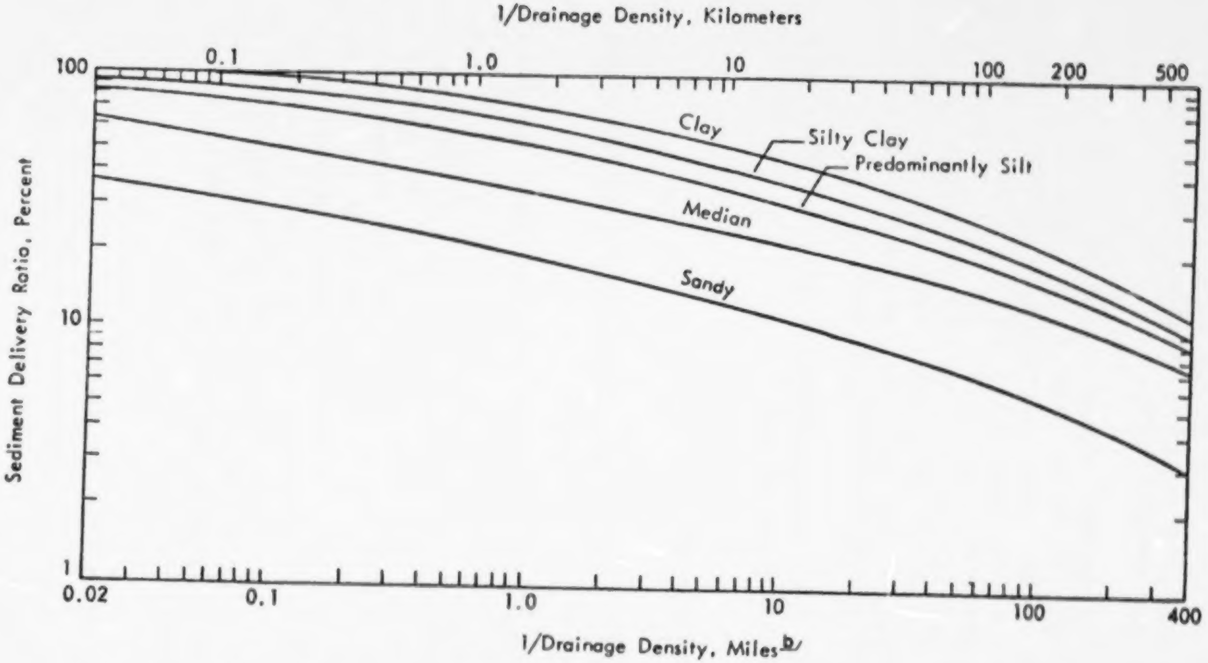
Chen's "micro model" for evaluation of erosion controls is based upon the following equation:

$$Qc = R\ K\ LS\ C$$

where Qc is the soil loss from construction lands; and
C is the "control practice."

This is basically the USLE without the sediment delivery ratio, and with the C and P terms combined into a single control practice index. The nomograph developed by Chen for evaluating this equation is reproduced here as Figure 17. Working from left to right, the values of R, K, and LS are utilized to determine the soil loss from the construction site without control (axis 5). Relating this to the maximum allowable rate of soil loss (from the macro model) yields the value of the control practice index C which must be achieved. The most important aspect of this approach is the disaggregation of C into control "factors" which are associated with individual physical measures. The following relationship is specified:

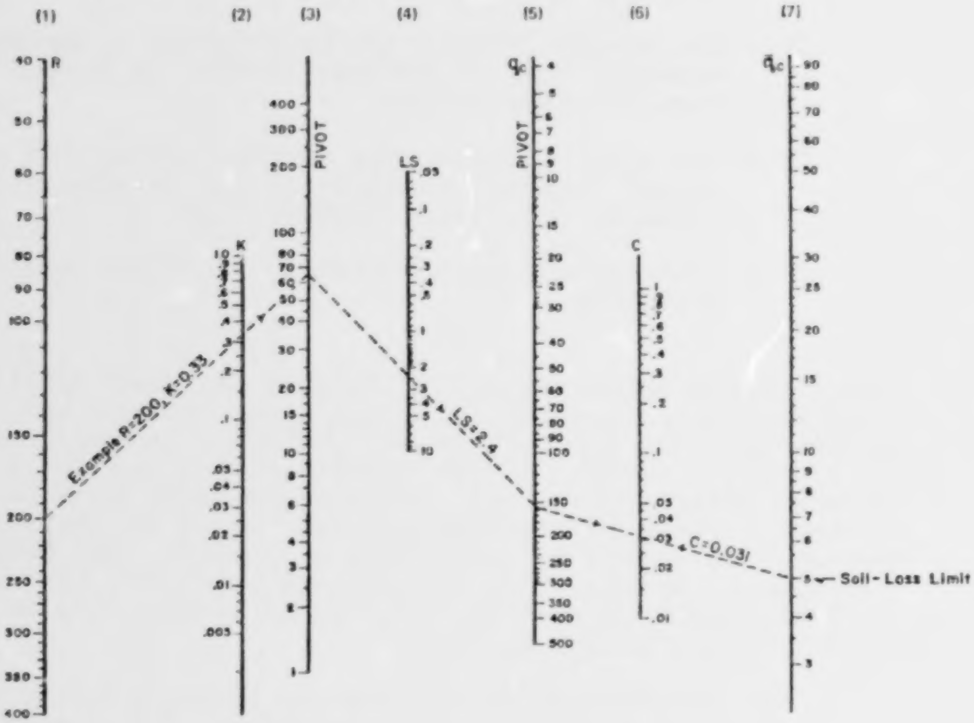
$$C = Cs\ Cr\ Ct\ Ce\ Co$$



a/ Source: Midwest Research Institute, "Interim Report on Loading Functions for Assessment of Water Pollution From Nonpoint Sources," EPA, Washington, D.C., November 1975.

b/ Drainage density equals total channel length (accumulated for all orders within a basin) divided by the basin area.

Figure 16 SEDIMENT DELIVERY RATIO FOR RELATIVELY HOMOGENEOUS BASINS



NOMENCLATURE

R - Rainfall Erosion Factor per Period (EI, or Erosion index Values
K - Soil Erodibility Factor (Ton/Acre/EI Value)
LS - Slope-Length Factor
C - Control Practice Factor
q_c - Erosion Rate without Control Practice (C=1) Ton/Acre/Period
$\bar{q}_c$ - Erosion Rate with Control Practice (Ton/Acre/Period)

Source: Chen, C.N., 1974

Figure 17 NOMOGRAPH FOR ON-SITE EROSION CONTROL PLANNING

where:

Cs = the control factor due to surface stabilizing or protective treatments such as seeding, mulching, and netting;

Cr = the control factor due to runoff-reduction practices such as diversion berms, interceptor dikes, benches and terraces, sodded ditches, and level spreaders;

Ct = the control factor due to sediment trapping measures such as sediment basins or basins with chemical flocculants;

Ce = the control factor due to restricting the spatial and/or temporal exposure of the denuded site to rainfall and runoff erosion; and

Co = control factors associated with other additional practices.

Quantitative information on C factors has been developed from available research and field data. Charts and graphs presenting this information are contained in the reference cited (Chen, 1974). A good example of the manner in which various control practices can be combined to produce a desired C value is provided by Chen, based on the situation depicted in Figure 17, for which C = 0.031. The measures considered include surface stabilizing treatments, runoff control measures, sediment traps, and limitations on the extent of ground exposure.

> "The denuded ground surface can be temporarily protected by properly tacked mulching. For instance, a control factor, Cs, of 0.2 can be achieved by applying roughly 1 ton per acre of straw, 7 tons per acre of woodchips, or 120 tons per acre of crushed stone or gravels (see Figure 7 in Chen, 1974). The erosion process can be further checked by runoff-control measures such as diversions across the slope. A single diversion ditch cutting across the 300-foot length at mid-slope, for example, provides a control factor, Cr, of 0.7 (see Figure 8 in Chen, 1974). Additional protection can be achieved by trapping the sediments

> eroded from the slope. If a sediment basin of 20 acre-inch capacity is available at the downstream end of the 50-acre site, the basin provides a control factor, Ct, of 0.36 (see Figure 9 in Chen, 1974). The overall control factor due to the combined practices of mulching, diversion and basin trapping is the product of Cs, Cr and Ct, or 0.050. Since this overall C factor is greater than the required value of 0.031, the system of control measures does not constitute an acceptable practice under the given control criterion.
>
> "Further reduction of the erosion can be achieved by establishing vegetative growth (such as annual rye-grasses) by increasing the mulch rate, by increasing the number of diversions, or by limiting the extent of grading operations within the development site. For example, a control factor, Ce, of 0.35 can be obtained by proper scheduling of the grading operation such that the overall exposed area is limited to 60 percent of the site and the site is denuded from October to June, avoiding the highly erosive months of July and August (see Figure 10 in Chen, 1974). This additional control practice with Ce = 0.35 brings the overall control factor down to 0.018. This is considerably lower than the required value of 0.031. If the scheduling practice is workable from the management point of view, then the overall control factor requirement of 0.031 can be satisfied without even considering the runoff-diversion measure. This demonstrates the flexibility of the tool presented herein in planning on-site conservation practices."

This methodology might also be used in developing construction site controls based on pollutants other than sediment. The most important case would be phosphorus, which is closely associated with sediment loadings. For example, suppose that study of eutrophication problems in a reservoir indicates that phosphorus loadings must be controlled to 0.5 lbs per acre per year from the catchment area of the reservoir. This area is undergoing extensive development, with 30% of the land in construction sites. Available data indicate that the phosphorus yield due to soil loss from non-construction land amounts to 0.2 pounds per acre per year, which is not considered controllable in this particular case.

Suppose it is determined that the phosphorus-to-sediment ratio is approximately 0.00005:1. To meet the phosphorus limit, the total sediment loading to the reservoir must then be restricted to 5 tons per acre per year (equal to 0.5/2000 /0.00005). Assuming a sediment delivery ratio of 0.4, the total allowable soil loss from land surfaces in the catchment would be 12.5 tons per acre per year. Of this amount, 1.4 tons per acre per year would be accounted for by non-construction land (computed using the same phosphorus-to-sediment ratio). Thus, the total allowable soil loss from construction sites would be equal to: 11.1/0.3 = 37 tons per acre per year. This maximum soil loss would be compared with the expected soil loss without control, as determined from Figure 17, in order to establish the control practice C. Analysis of the controls necessary to achieve the given value of C would then proceed as indicated above.

An alternative approach in applying the USLE might be to consider soil loss only, not the sediment loadings delivered to specific points in surface waters. The following arguments would favor such an approach.

1. Soil loss may be a good overall statement of erosion impact since all material eroded from construction sites is potentially problematic, whether or not it reaches a given receiving water body.

2. Selection of a stream point as a basis for computing allowable loadings may represent a somewhat arbitrary decision; and quantitative description of allowable in-stream conditions may be difficult, in view of the extreme variability of sediment concentrations.

3. Linkage of allowable soil loss to receiving waters will increase the variability among areas in the degree of control required (C), and thus may add to enforcement difficulties and the possibility of challenge on equity grounds.

A reasonable approach may therefore be to select one or more regional values of allowable soil loss (Qc) and to use these as a basis for design of control measures. Sample computations of in-stream loadings would perhaps be conducted to demonstrate that these values of Qc would provide adequate overall protection of water quality. The control practice index C would then be computed for individual construction sites using the formula:

$$C = \frac{Qc/R}{K\ LS}$$

Within the region to which Qc applies, the variable factors affecting control practice would be the terms in the denominator, K and LS, pertaining to soil erodibility and slope length and gradient.

A general characteristic of the USLE is that soil loss is typically most sensitive to slope gradient. (The LS factor varies roughly as the 0.5 power of slope length, and as the 1.5 power of slope gradient.) Differences in steepness of slope can produce order-of-magnitude differences in computed soil loss from small land areas. For example, a recent watershed study in Philadelphia by Coughlin and Hammer (1973) utilized the USLE to predict soil loss due to construction, without control measures, for a large number of 5-acre grid cells. The computed values of soil loss are tabulated here in Table 16. The degree of variability is striking, in view of the fact that the soil erodibility factor K ranged only between 0.28 and 0.43. The predicted annual soil loss was less than 100 tons per acre in more than 10% of the cases, but greater than 2,000 tons per acre in 5% of the cases. If the approach mentioned above had been utilized, and if the allowable soil loss had been set at 30 tons per acre per year, the appropriate control practice index would have varied from 1.0 to less than 0.01. Although this example is somewhat extreme, in that much of the steep land with high soil loss potential would not be considered suitable for building in any case, it is important to note that direct application of the USLE can lead to widely different levels of control for construction sites within a given vicinity.

Control of Hydrographic Modification due to Construction

An impact of construction activity which is often not given explicit consideration is the increase in runoff quantity which occurs during the construction phase. Elimination of vegetation, compaction of the soil, and exposure of subsoil during construction may increase runoff very substantially, in some cases by amounts which are as great or greater than the effects of completed development. Thus, erosion/sedimentation control plans should include measures which reduce peak rates of runoff as well as sediment loads. This may involve design of sedimentation basins and other structures so that detention storage capacity is adequate to control peak discharge in moderately severe storms. The S.C.S. materials referenced in Section 9 can be utilized for this purpose.

TABLE 16

COMPUTED SOIL LOSS FROM 5-ACRE GRID CELLS
IN THE WISSAHICKON WATERSHED, PHILADELPHIA

Range of Soil Loss in tons/acre/year	Number of Grid Cells	Percent of All Cells
Less than 50	14	1.4%
50 - 99	92	9.3
100 - 199	176	17.8
200 - 499	284	28.6
500 - 999	215	21.7
1000 - 1999	162	16.3
2000 or more	49	4.9
	992	100.0%

Implementation of Erosion/Sedimentation Controls

Control of erosion problems due to construction is considered an extremely important aspect of water quality planning; and there are a number of favorable circumstances which should assist in implementation of these measures. The problem is widely acknowledged, and is already subject to control in a number of U.S. areas. The expense incurred by builders in meeting erosion control regulations is usually small relative to total project cost. Although the magnitude of the problem and the effectiveness of control measures are often difficult to quantify accurately, regulations are not highly vulnerable to challenge on technical grounds, since there is not a question of "threshold" effects. Even small sediment loadings are potentially important; thus it is difficult to argue that control in a particular case is unjustifiable.

A major issue which has been touched upon earlier is the extent to which the degree of control should vary among construction sites. If controls are based upon predetermined values of allowable soil loss or stream impact, the requirements are likely to vary widely in terms of the physical control measures which builders must provide. This situation could arise even if the factors which distinguish between sites are not treated explicitly in official regulations, since approval of specific erosion/sedimentation plans by enforcement agencies might be based upon computations using the USLE. The potential problem is that control programs which discriminate strongly among sites might be considered inequitable.

An alternative approach is to apply erosion/sedimentation controls more or less uniformly (e.g., to specify requirements in terms of the control index "C," rather than in terms of soil loss) and to deal with the most problematic areas through land use control. Restriction of development on steep slopes is the most prominent example. An implicit basis for this approach may be the view that, in cases where highly elaborate countermeasures would be required to prevent erosion during construction, adequate performance by the developer would be very difficult to assure through normal monitoring and enforcement procedures. Limitation of development *per se* might be a safer approach, and could yield a variety of benefits such as preservation of scenic hillslopes. One problem is that, since known methods can potentially prevent erosion from almost any buildable site, land use restrictions might be difficult to justify on the basis of erosion alone if challenged. Thus, land use controls should be linked explicitly to other objectives in addition to erosion control, and should preferably be supported by a comprehensive environmental inventory and analysis.

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